District 1 Climate Change Vulnerability Assessment and Pilot Studies

FHWA Climate Resilience Pilot Final Reports

December 2014

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13. ABSTRACT This report presents the results of a Climate Resilience Pilot Project conducted by the California Department of Transportation (Caltrans) District 1 and sponsored in part by the Federal Highway Administration. The objective of the study was to identify and classify the potential vulnerabilities of state owned transportation assets to climate change throughout District 1, which encompasses the counties of Del Norte, Humboldt, Mendocino, and Lake in north western California; and to identify and evaluate a range of adaption options to address the identified vulnerabilities at four prototype locations. The study involved the creation of a process for evaluating the vulnerability of Caltrans transportation assets in District 1 due to various climate change factors and development of a tool to assess adaptation strategies for vulnerable assets.		
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1. Executive Summary

This report presents the results of the California Department of Transportation (Caltrans) District 1 Climate Change Pilot Study (D1CCPS). The objective of the study was to identify and classify the potential vulnerabilities of state owned transportation assets to climate change throughout District 1, which encompasses the counties of Del Norte, Humboldt, Mendocino, and Lake in north western California; and to identify and evaluate a range of adaption options to address the identified vulnerabilities at four prototype locations.

The study involved the creation of a process for evaluating the vulnerability of Caltrans transportation assets in District 1 due to various climate change factors and development of a tool to assess adaptation strategies for vulnerable assets.

Figure 1 shows the general process followed for the study. The overall process progressed through the following stages of analysis: criticality, exposure, Potential for impact, vulnerability, and adaptation. Information on each of these steps is presented below in this executive summary, followed by information on findings, lessons learned, and next steps.

This report follows the format set out by the Federal Highways Administration for Climate Resilience Pilot Adaptation Projects. This report acts to summarize the activities conducted in the study. More detail on all activities can be found in the Appendices to this Report, which include technical memorandums completed throughout the project.

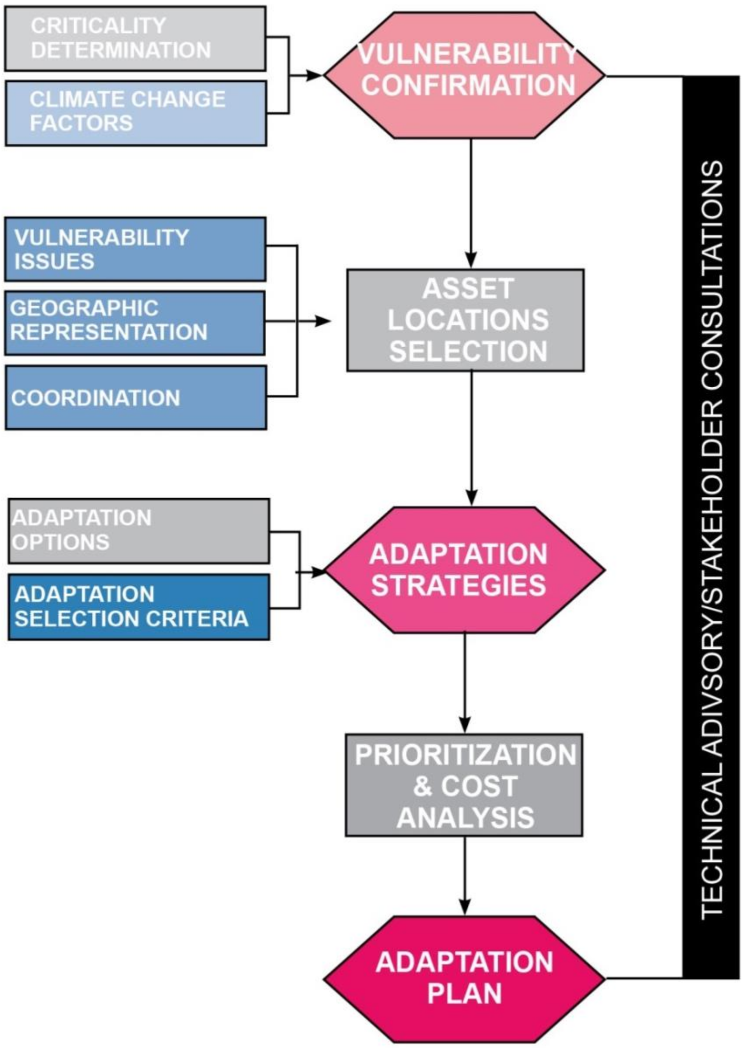


Figure 1: Overall Project Flow Chart

1.1 Vulnerability

Vulnerability is defined by the Intergovernmental Panel on Climate Change (IPCC) as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes”. The vulnerability assessment, described below, combined consideration of criticality (including socioeconomic, operational, and health and safety importance), exposure to climate change effects, and potential for impact (including exposure, sensitivity, and adaptive capacity).

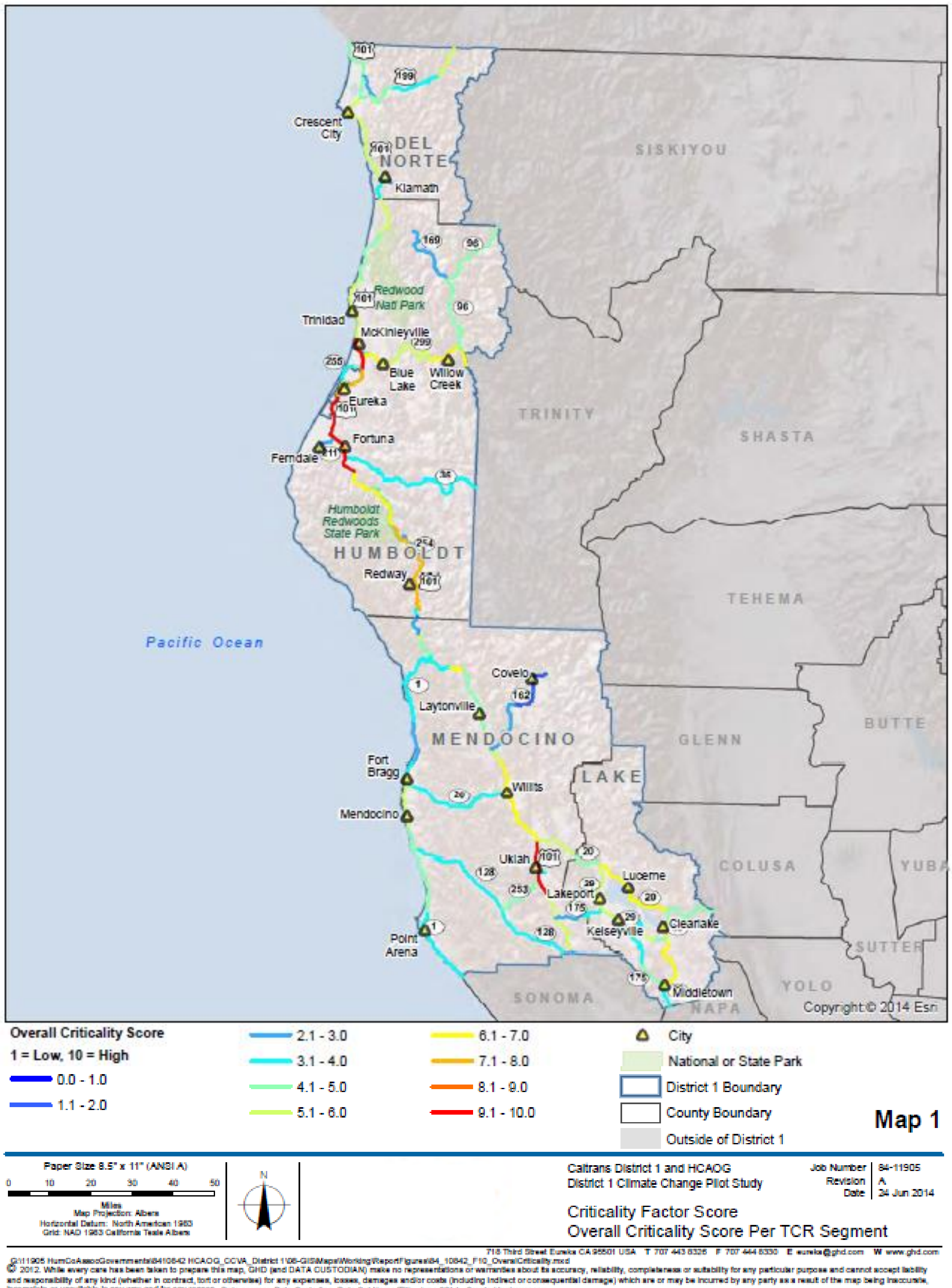
For analysis purposes, the state highway system was divided up into road segments. All assets within a roadway segment were considered as one unit. Segmentation based on Caltrans Transportation Concept Report (TCR) road segments, was selected because the TCR strategy is commonly associated with broader transportation planning similar to the efforts in this study, and to align the data produced in this study with future efforts conducted by Caltrans.

The most vulnerable road segments were identified by combining the criticality and potential for impact findings. A prototype location was selected for each county; these sites provided the project team with the ability to develop adaptation alternatives to address the effects of climate change. Each of the components of vulnerability is described in more detail below.

1.1.1 Criticality

Criticality in this report is defined as the relative importance (as established by local stakeholders) of a transportation facility or asset in comparison to equivalent facilities. Relative importance of a facility considers the degree to which a facility provides socioeconomic functions (e.g. access to major employment centers or business districts), use and operational characteristics (e.g. average daily traffic or functional classification), health and safety functions (e.g. access to medical facilities or evacuation routes), replacement costs (e.g. number of large bridges or length/width of highway segment), and degree of redundancy (i.e. parallel assets that can provide equivalent functions). Criticality of assets was evaluated based on quantitative and qualitative criteria, which were ranked by the Technical Advisory Group (TAG) and Stakeholder Group (SG) for local relevance.

These rankings helped to scale the relative importance of factors. Each roadway segment was then evaluated for its relative criticality in comparison to other state highway segments in District 1. Based on this process, the most critical road segments were found to be around Humboldt Bay/ Lower Eel River communities (Humboldt County), with other clusters around Ukiah (Mendocino County). Map 1 shows the criticality rankings of roadway segments in District 1.


Pacific Ocean
DEL NORTE
SISKIYOU
TRINITY
SHASTA
HUMBOLDT
TEHEMA
MENDOCINO
GLENN
BUTTE
LAKE
COLUSA
YUBA
SUTTER
YOLO
SONOMA
NAPA
Crescent City
Klamath
Redwood Nat'l Park
Trinidad
McKinleyville
Blue Lake
Willow Creek
Eureka
Fortuna
Ferndale
Humboldt Redwoods State Park
Redway
Covelo
Laytonville
Fort Bragg
Willits
Mendocino
Ukiah
Lucerne
Lakeport
Kelseyville
Clearlake
Point Arena
Middletown
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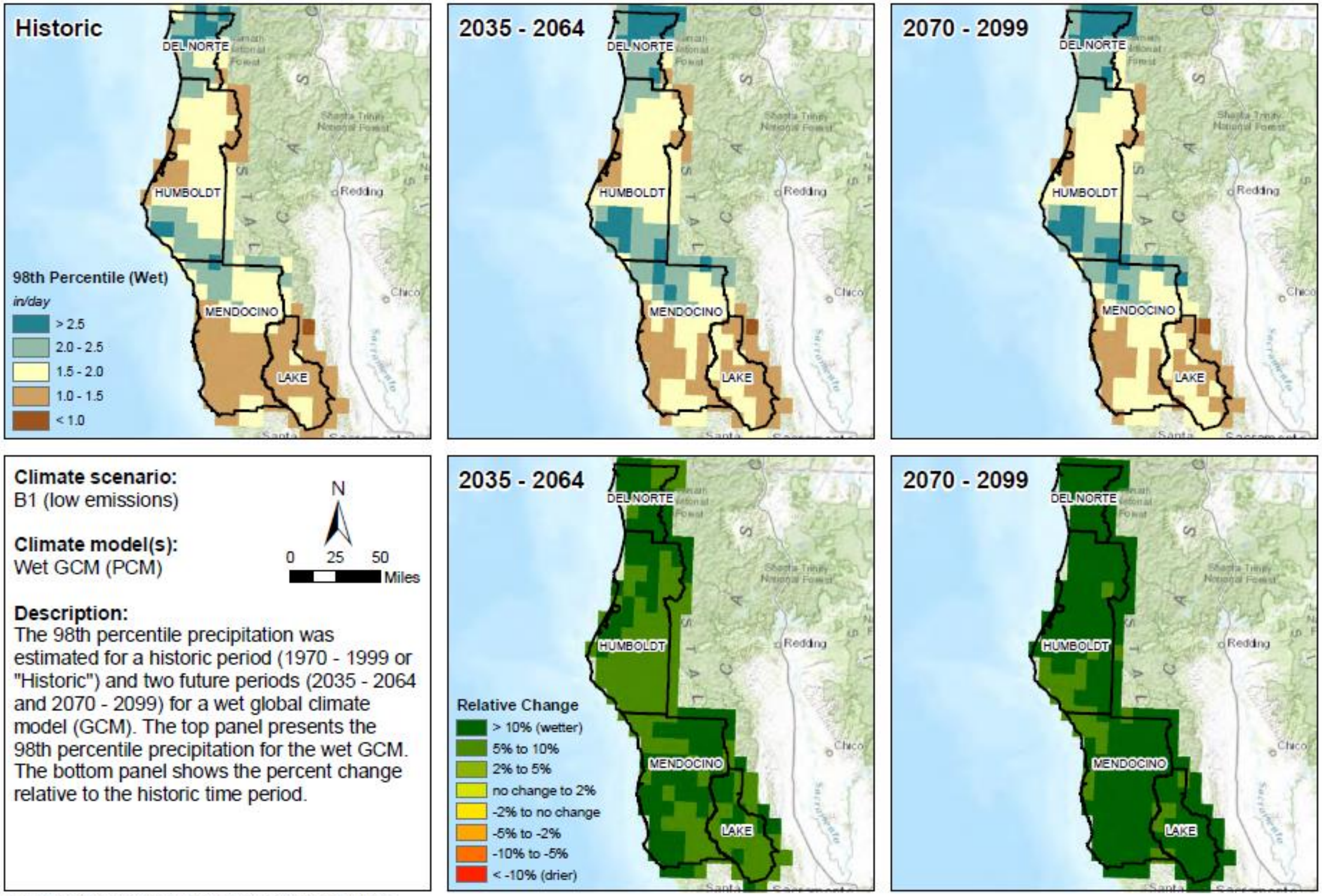
Overall Criticality Score
1 = Low, 10 = High
0.0 - 1.0
1.1 - 2.0
2.1 - 3.0
3.1 - 4.0
4.1 - 5.0
5.1 - 6.0
6.1 - 7.0
7.1 - 8.0
8.1 - 9.0
9.1 - 10.0
City
National or State Park
District 1 Boundary
County Boundary
Outside of District 1
Map 1
Paper Size 8.5" x 11" (ANSI A)
Miles
Map Projection: Albers
Horizontal Datum: North American 1983
Grid: NAD 1983 California Teale Albers
Caltrans District 1 and HCAOG
District 1 Climate Change Pilot Study
Job Number 84-11905
Revision A
Date 24 Jun 2014
Criticality Factor Score
Overall Criticality Score Per TCR Segment

1.1.2 Exposure

Evaluation of the exposure of Caltrans transportation assets in District 1 to a range of climate stressors is a key component of the vulnerability assessment. Projecting potential climate trends and extremes requires first establishing future scenarios of GHG emissions which will influence future climate patterns. Due to the high level of uncertainty in the evolution of these factors, multiple projections over various timeframes have been modelled. For this study, the exposure of transportation assets to forecasted climate change was the based on two emissions scenarios, and two timeframes (2050 and 2100). One emissions scenario, called B1, assumes carbon emissions are reduced within 100 years. The other scenario, called A1, assumes that there is no decrease in carbon emissions.

Changes in temperature, precipitation, runoff, and sea level rise were modelled for the four county study areas under the four GHG/ timeframe scenarios. In general, the scenarios showed increases in temperature, with greater increases inland than at the coast. Rainfall and runoff changes varied depending upon models. Models predicting increased rainfall were used as a conservative measure to assess asset exposure. Sea level is also predicted to increase, with a greater rate of increase in the Humboldt Bay region due to subsidence and tectonic patterns. Map 2 show an example of the regional exposure assessment for changes in the 98th percentile precipitation.



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Caltrans District 1 Climate Change Pilot Study . 130588.00

SOURCE: Cal Adapt, 2014

Map 2

98th Percentile Precipitation: Average Values and Relative Change for Scenario B1, Wet Model

1.1.3 Potential for Impact

Potential for impact was assessed by using historical maintenance events and the exposure data described above to classify road segments according to the likelihood of future reduced capacity, temporary operational failure, or complete failure. Road segments with the highest potential for impact, or greatest likelihood of complete failure, tended to be located in flood zones or areas of steep coastal cliffs where there were either historical slope movements or other erosion hazards. These road segments were in Del Norte, Humboldt, and Mendocino Counties. Figure 2 shows the scoring for roadway potential for impact.

POTENTIAL FOR IMPACT TO DISTRICT INFRASTRUCTURE									
REDUCED CAPACITY			TEMPORARY OPERATIONAL FAILURE			COMPLETE FAILURE			
1	2	3	4	5	6	7	8	9	10
• Minor repairs consistent with routine maintenance. • Potential minor roadway speed reduction, brief traffic control measures and brief delays in access.			• Moderate repairs and replacements required • Traffic delays and/or traffic control measures for extended periods (hours to days), temporary re-rerouting of traffic, and potential for vehicle stranding.			• Significant impact requiring reconstruction of a part of whole asset. • Extensive rehabilitation of assets, significant reduction of travel for extended periods of time and significant safety and stranding issues			

Figure 2: Scoring Criteria for Potential for Impact

1.1.4 Vulnerability Summary

Vulnerability was evaluated as a product of criticality and potential for impact, which incorporates exposure. The criticality and potential for impact scores were multiplied together to calculate a resulting score up to 100, with a lower score reflecting lower resulting vulnerability. Vulnerability was calculated for each of the two emissions scenarios and two timeframes.

Figure 3 provides a visual of the relationship between criticality on the horizontal axis and impact on the vertical axis with increasing vulnerability moving towards the upper right hand corner in the red zone.

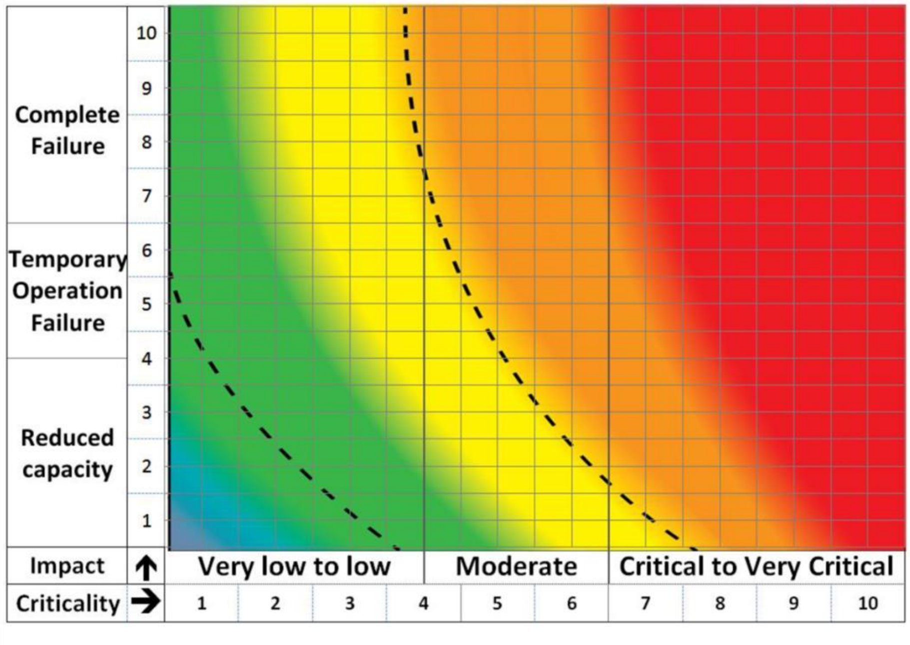

Figure 3: Vulnerability Heat Map

The most vulnerable road segments were identified by combining the criticality and potential for impact findings. A prototype location was selected for each county; these sites provided the project team with the ability to develop adaptation options to address the effects of climate change.

Map 3 shows the final vulnerability rating for roadway segments for 2050 under the A2 high emissions scenario.

Overall Vulnerability Score
Low = 1, High = 100

- 1-10
- 10.1 - 20.0
- 20.1 - 30.0
- 30.1 - 40.0
- 40.1 - 50.0
- 50.1 - 60.0
- 60.1 - 70.0
- 70.1 - 80.0
- 80.1 - 90.0
- 90.1 - 100.0
- City
- National or State Park
- District 1 Boundary
- County Boundary
- Outside of District 1

Map 3

Paper Size 8.5" x 11" (ANSI A)

0 10 20 30 40 50
Miles
Map Projection: Albers
Horizontal Datum: North American 1983
Grid: NAD 1983 California Teale Albers

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Caltrans District 1 and HCAOG
District 1 Climate Change Pilot Study

Job Number 84-11905
Revision A
Date 01 Jul 2014

Climate Horizon 2050 A2
Overall Vulnerability Score Per TCR Segment

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The final four prototype locations were:

- Del Norte County, Hwy 101, from Post Mile 14.2 to 15.6, also known as Last Chance Grade.
- Humboldt County, Hwy 101, from Post Mile 79.3R to 85.3, also known as the Eureka Arcata Corridor
- Lake County, Hwy 20, from Post Miles 52.5 to R47.9 and CR 407(Nice-Lucerne Cut off).
- Mendocino County, Hwy 1, from Post Mile 17.5 to 18.6. Area around the Garcia River Bridge.

1.2 Adaptation

The vulnerability assessment focused on primary climate change effects such as temperature and precipitation, and projected the potential impacts of secondary effects such as erosion, flooding, and landslides. Road managers already contend with these climate-related impacts; climate change alters the frequency and intensity of them. The adaptation phase of work studied the secondary effects on the four prototype vulnerable road segments and provided a framework to evaluate alternatives (adaptation options) that defend the road (i.e. armouring), adapt the road (i.e. elevate), or plan for retreat out of hazard zones (i.e. relocation). This framework also included consideration of a “do nothing” scenario, and policy changes that could have bearing on future project decisions.

Evaluative criteria for these adaptation options included cost, usable life, level of performance, flexibility of design, and social and environmental considerations. Estimating project implementation timeframes assisted in understanding the usable life of an adaptation option in light of climate change time thresholds. A tool was developed to assist planners with the selection and evaluation of adaptation options. This tool was developed and then tested on the four prototype locations. Table 1 shows the broad categories of adaptation options considered.

Table 1: Adaptation Option Categories Developed from Adaptation Tool

Approach	Adaptation Option
Defend	Provide major structural protection
	Provide protection at existing elevations/locations
Accommodate	Elevate the infrastructure above the impact zone
	Enhance drainage to minimize closure time and/or deterioration levels
Retreat	Abandon infrastructure
	Relocate infrastructure (horizontally)
	Temporarily restrict use of infrastructure
Changes in policies or practices	Increase the infrastructure's maintenance and inspection interval and continue to monitor/evaluate

	Modify land use and development policies to account for future impacts

1.3 Findings

Climate change will predominately impact District 1 roads through sea level rise and increased coastal erosion hazards, Inland roads will tend to be more affected by hazards related to increased precipitation, although sea level rise can affect inland roads through backwater effects on rivers. Preparing for these climate-change driven events will require further planning and evaluation to select the best approaches to be implemented at the most opportune time. The tools and the work completed for the prototype locations provided a process and an initial foundation for further work.

The process of completing this study resulted in a number of valuable findings that can help direct the future climate adaptation work. These findings were ranging from planning for changes in maintenance and design practices to more detailed analysis of vulnerable assets. Three primary actions identified to build on the results of this study are summarized below:

1.3.1 Coordination with Public Agencies and Private Landowners

Through this study, a better understanding of the dependencies between Caltrans assets and nearby public and private assets was gained. As Caltrans moves forward on climate change adaptation planning, it will be important to collaborate with other local and state agencies as well as private land owners. It will be important to consider cost efficiencies and multiple benefits to other vulnerable infrastructure when planning for adaptation of the transportation system.

1.3.2 Changes to Caltrans Planning and Design Policies

Caltrans should consider working with the Federal Highways Administration, FEMA, and other agencies to update design standards to be more reflective of potential climate change and provide more adaptive capacity within new structures built.

Local maintenance staff are at the forefront of addressing the effects of extreme weather events today, and the on the ground knowledge can be better captured. Caltrans should consider updating the maintenance and repair data collection and tracking systems to include more site and event specific data such as precipitation conditions prior to maintenance events, location and type of maintenance activity, more detail on the type and mode of asset failure, and specific event dates will help Caltrans understand priority vulnerable assets better

1.3.3 Site Specific Risk Analyses

The effects of climate change are not uniformly distributed across Caltrans assets and the effects are often intermittent. The effects can be magnified through multiple forces converging simultaneously. It is not logical to simply combine a series of possible events into a "worst-case scenario" and design for that because, although the effects may be very dramatic, the likelihood may be very low. It is recommended that more detailed studies at highly vulnerable locations be conducted which incorporate a statistically based approach to simulate the combined likelihood and resulting effects. Through techniques such as a computer-based Monte Carlo Simulation, many thousands of iterations can be run and the results analyzed to evaluate the potential for combined effects. This can also be linked to a damage estimate model and an adaptation cost model to select economical adaptation strategies and appropriate implementation timelines.

1.4 Conclusions

This project advanced awareness of the climate change risks posed to communities and infrastructure, and provoked enlightening discussions about planning, criticality, and the future of the state road system. Tools were developed that provide partial automation of data processing and can expedite the assessment of climate risks to different kinds of infrastructure. Findings from the project are informing existing projects and demonstrating opportunities to leverage resources.

The project inventoried and analyzed over 16,000 Caltrans assets against a 2050 and 2100 climate change threshold and 2 climate models. Ninety-three road segments representing almost 980 miles over 23 Caltrans roadways were ranked for vulnerability using weighting and scoring criteria scaled with input of TAG and Stakeholders. Adaptation options for four pilot project sites were also scored using weighted criteria informed by input of TAG, Stakeholders and members of the public. Twenty-four members of the TAG, 59 stakeholders, and 119 members of the public were reached during the project process.

Proposed adaptation projects would prevent strandings and ensure high level of service in Pt Arena/Stornetta area; maintain a lifeline to Crescent City; reduce traffic diversions and disruptions of service in Humboldt Bay; and minimize re-routing and delays in Lake County.

Findings from this study are supporting current studies on Highway 101 at Last Chance Grade in Del Norte County and informing dialogues on design on a planned interchange on Highway 101 in Humboldt Bay. The adaptation options explored in Mendocino County are providing information to assist the local transportation planning agency, Mendocino Council of Governments, in their assessment of routing options over the Garcia River. Findings for the Lake County road segment can be used by agencies working on Middle Creek/Rodman Slough restoration to inform their planning. Climate change vulnerability findings at the regional scale will be a reference tool for local transportation planning agencies in District 1.

2. Introduction to the Project

2.1 Goals

The goal of the project is to develop a methodology for addressing the impacts of climate change for a set of select prototype conditions. The adaptation methodology can serve as a model for other regions with their own unique characteristics, to use in their climate change adaptation planning efforts. The purpose of the project is to expand on previous efforts to systematically identify adaptation strategies for vulnerable assets, including short and long-term adaptation strategies for specific prototype locations that exhibit characteristics typical to many other regions of the United States.

The project includes conducting an inventory of Caltrans-owned assets (e.g. highways, bridges, other highway system infrastructure and facilities), identifying assets with known vulnerabilities to climate change impacts and severe weather, and assessing adaptation options at four prototype locations. FHWA has developed a methodology for conducting vulnerability assessments, which the Washington Department of Transportation has tested and refined (WSDOT, 2011). This project builds upon the existing FHWA and WSDOT methodologies and on existing climate change data.

Four proposed prototype locations were selected based on geographic and climate-related factors and criteria such as proximity to sea-level, susceptibility to flooding, geologic instability, and local connectivity. These four sites were evaluated for an array of short and long-term adaptation/ mitigation measures developed to address climate change impacts at each location. Assessing and responding to climate change impacts at the proposed prototype locations involved public outreach to culturally distinct and geographically disperse population centers.

The overall tool and process presented in this analysis could serve as models for similar transportation facilities and environmental conditions in California and the country. The use of these tools and methodology for identifying vulnerable assets and assessing adaptation options can be used by communities to help increase resiliency to the impacts of climate change and severe weather.

2.2 Report Format

This report follows the format set out by the Federal Highways Administration for Climate Resilience Pilot Adaptation Projects. This report acts to summarizer the activities conducted in the study. More detail on all activities can be found in the Appendices to this Report, which include technical memorandums completed throughout the project.

2.3 Scope

The project encompassed the four county area of Caltrans District 1: Del Norte, Humboldt, Mendocino and Lake Counties (see Map 4). Compared to the other areas of California, these are mountainous, relatively low population, rural counties. The state road system provides critical access between this region and the rest of the state; loss of Highways 1, 101, 20, 36, 299, and/or 199 would effectively isolate populations. Humboldt Bay and lower Eel River Valley communities experienced this in the aftermath of the 1964 floods. Last Chance Grade in Del Norte County has also experienced restricted access due to landslides. Any alternate route for residents of that area would take hours to reach other populated areas. Coastal Mendocino County residents contend with similar coastal erosion hazards. In both Lake and Mendocino Counties, flooding in low agricultural valleys can also halt traffic, leaving community members stranded. Lake County is more fortunate, with alternate routes for many of these areas.

Climate change is predicted to intensify existing hazards and in some cases may overwhelm current protective infrastructure. Extreme temperatures will increase, particularly in inland, mountainous areas. Coastal temperatures will remain more moderate. Sea levels are predicted to rise by as much as 4.6’ by 2100 (ESA, 2014). While models indicate variability in rainfall changes, the wetter scenarios were evaluated so that Caltrans could prepare for potentially more severe conditions.

The project scope proceeded according to the following tasks and flow chart. A complete scope of work can be found in **Appendix 10.**

2.3.1 Technical Advisory Group, Verification and Outreach

The D1CCPS project sought different levels of comment and guidance throughout the project from technical experts and members of the public as an essential part of the planning process:

Form Technical Advisory Group. A Technical Advisory Group, or TAG, was composed of transportation experts with interest and expertise in maintaining the state system. TAG members reviewed and critiqued project progress, contributed to rankings of assessment tools, and contributed ideas and knowledge to the overall process. Five TAG meetings were scheduled for this project. A stakeholder group (SG) was also established to confer with and seek input from other regional land managers and jurisdictions who were not necessarily transportation experts. Four Stakeholder Meetings were conducted.

Public Meetings. Public meetings were conducted in each county, mid-way through the project. The intent of these meetings was to update the public on the project and seek input on adaptation priorities and criteria.

Website A project website was created with two levels of access: password protected access to draft documents for the TAG and SG, and an open website with final documents and presentations for the general public. The website address is http://www.northcoastclimatechange.com.

Functional Classifications

- Freeway or Expressway
- Principal Arterial
- Minor Arterial
- Major Collector
- Local Road
- City
- National or State Park
- District 1 Boundary
- County Boundary
- Outside of District 1

Map 4

Paper Size 8.5" x 11" (ANSI A)

0 10 20 30 40 50

Miles
Map Projection: Albers
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Caltrans District 1 and HCAOG
District 1 Climate Change Pilot Study

Vicinity Map

Job Number	84-11905
Revision	A
Date	24 Jun 2014

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2.3.2 Vulnerability Confirmation

Vulnerability was confirmed by assessing asset criticality, or how essential an asset is; scaling climate change predictions to the regional level, and determining the potential for a road segment to be impacted by a climate event. The approach can be summarized in the following steps:

1. Conduct an inventory of Caltrans-owned transportation assets in District 1 for review.
2. Gather information on climate change projections of sea level rise, temperature changes, precipitation changes, and storm surge together with associated hazards such as erosion, flooding, landslide, and fire within District 1. Consult with Caltrans staff on prior extreme weather impacts.
3. Establish qualitative criteria for initial screening for both asset criticality and vulnerability.
4. Undertake qualitative screening by appropriate subject matter experts and input from the TAG and stakeholders to assess and prioritize asset criticality and vulnerability.
5. Create a GIS map showing the assets, their criticality, and vulnerability.
6. Confirm and refine the four prototype locations on the GIS map.

Collect Data and Assess Vulnerability.

A targeted inventory of Caltrans assets including storm drains, culverts, bridges, buildings and other assets were collected. Much of this data was available in Geographic Information Systems (GIS) format. Historical maintenance data was also obtained and analysed. TAG members were consulted to clarify and refine the data. Quantitative and qualitative criteria for evaluating criticality and potential for impact were developed. An Exposure analysis was conducted through down-scaling of global climate models to the regional level. GIS-based climate change information on sea level rise, storm surge, temperature, and precipitation for both mean and extreme conditions was overlaid on the asset data to evaluate the potential for impact, defined as the level of interruption of service of the asset. Combining these factors led to the overall vulnerability assessment. These findings were reviewed by the Project Management Team, TAG, and SG.

Confirm and Refine Project Areas for Adaptation Work

The vulnerability assessment ranked road segments. The most vulnerable segments in each county were identified, along with the climate criteria contributing to that ranking. These criteria were shared with the PMT for selection of project areas for adaptation planning. Selected adaptation sites exhibited vulnerability to climate change effects such as sea level rise inundation, coastal or bluff erosion, and lake or river flooding that are typical causes of impacts to the region’s transportation assets. This allowed the Project Team to explore a range of situations and adaptation options with planning attention distributed equitably across the region.

2.3.3 Adaptation Assessment

Under adaptation assessment, the identified vulnerabilities at the prototype locations were used to develop a number of candidate actions Caltrans could implement to adapt to changing climate conditions. Adaptation strategies were generally focused on engineering based solutions, including structural modifications, operational strategies, design standards, and technology improvements. In addition, opportunities to incorporate ecosystem-based adaptation, such as using wetlands to reduce sea level rise impacts, as well as non-structural solutions, such as traffic routing, were investigated. Potential cost savings to the adaptation strategies and co-benefits of different approaches were captured through an evaluative tool and incorporated into option ranking. While “hard engineering” solutions are common, other approaches like policy changes were also considered.

Each adaptation strategy was evaluated with consideration of timeline, relative cost, flexibility, and potential for multiple benefits. In the final step, planning level cost estimates or cost comparisons were developed for the priority adaptation strategy at each prototype location.

Identify Adaptation Options

Good adaptation strategies are typically flexible, cost effective, address the specifics of the climate change impact, and integrate science with public and regulatory acceptability and support. Under this task the project team identified climate adaptation strategies that could be implemented at the four prototype locations. A preliminary list of adaptation options was developed from the project team’s existing knowledge base, which included information from the Humboldt Bay Sea Level Rise Adaptation Planning Working Group. This list was expanded through a thorough literature review, consultation with transportation agencies, consultations with state and local planning groups, and consultation with the TAG and PM Team.

Adaptation is described in terms of climate factor and anticipated effect impacting the infrastructure; options assessed; planning horizon (short term vs long term); and implementation timeline.

Develop Adaptation Assessment Criteria

The list of adaptation options compiled in Task 3A was compared with the needs and priorities at each of the prototype locations. A set of criteria was developed to evaluate the applicability of different strategies to the climate change impacts identified at the prototype locations. The criteria allowed comparison of the different asset adaptation options (including the no action scenario) to improve their resiliency to climate change. A range of potential criteria were reviewed and ultimately the were selected: total capital investment, equivalent annual cost, usable life, level of performance, flexibility, environmental considerations, social considerations.

Create Adaptation Assessment Methodology

An objective comparison and ranking of adaption options was developed with the suite of adaptation implementation options and assessment criteria. A uniform scoring system was developed to measure the ability of the adaptation option to address the vulnerability of the asset. Assigning weights and scoring the established criteria can be a highly subjective process, therefore the scoring system and weighting factors were based on technical research conducted in Task 3A and supported by opinions from relevant experts from the TAG, stakeholders, and public. A sensitivity analysis of the criteria and asset weightings was conducted to improve balance of weights and avoid dominance by a single assessment criteria or asset weighting.

Prepare Cost Analysis for Adaptation Options

After prioritization of the adaptation options, the highest priority option at each prototype location was further evaluated in terms of potential planning and implementation costs and possible funding sources. Any existing cost estimates available for proposed projects sites were improved to provide relevant and usable information to Caltrans. For example, existing maintenance costs in a "do-nothing" scenario were modelled for comparison to an adaptation option cost.

2.3.4 Final Report

The final report (this document) includes a summary documenting the work completed, which includes the methodology developed to assess adaptation options, developed assessment criteria, and prioritized adaptation options, as well as procedures for estimating costs of adaptation options. In addition, the final report includes:

- A summary of the work performed and deliverables produced (incorporation of Technical Memos)
- A description of the groups involved, including the TAG, PM Team, stakeholders, and the public; the roles and responsibilities of each of these groups will also be described
- Recommendations for future actions to improve climate change adaptation process and procedure for transportation agencies
- Best practices, lessons learned, issues encountered, and procedures used to address the issues

2.3.5 Training and Presentations

Conduct Presentation to Stakeholders

In the context of this project, the stakeholders represent a group of people and organizations that have potentially more to offer the project in terms of scientific knowledge and community leadership. Engaging this group in a more technical forum than may be appropriate for the general public was an important tool along with the engagement of the TAG to inform the development of climate change impacts, adaptation options, and adaptation assessment criteria. As discussed in Task 1B, it was envisioned that stakeholder meetings would be held in close proximity to the public meetings scheduled to gather input for key project components. The timing and location of stakeholder meetings and task deliverables was similar to the public meetings; see Task 1B for more information.

Provide On-Site Training

The consulting team, with input from the TAG and PM Team, will provide on-site training to interested stakeholders on preparing vulnerability and adaptation assessments that address climate change impacts and increase transportation facility resiliency to climate change and severe weather.

2.4 Partners

This project was completed for Caltrans District 1 in cooperation with the Humboldt County Association of Governments by GHD Inc. a global engineering and environmental consulting firm with an office located in Eureka the Caltrans District 1 Headquarters. The project was led by GHD with support from ESA, who provided technical expertise on climate change modelling and impacts, and with the support of Trinity associates who brought expertise in climate change modelling and impacts especially along the Highway 101 corridor between Eureka and Arcata. The Mendocino

Council of Governments, Del Norte Local Transportation Commission, and Lake City/County Area Planning Council, all local transportation planning agencies, were partners to the project who lent their expertise as members of the Technical Advisory Group and were consulted for public meeting planning and site-specific designs.

3. Approach

3.1 Data Gathering and Analysis

The approach begins with conducting an inventory of assets, considering the effects of climate change based on selection of appropriate models, and then integrating the data so that is can be used in the overall process.

3.1.1 Asset Inventory

Caltrans was the primary supplier of asset inventory data. **Appendix 1, Caltrans TCR Segment Criticality** describes the transportation assets, asset services, and indicators of needs of services that were accumulated as part of this study. TCR segments are described in Section 3.2.

Caltrans District 1 provided several GIS layers representing all significant "transportation assets" that were to be analyzed for this study. Transportation assets are defined as "existing physical entities that required capital investment upon their installation, that have current capital value, that would require capital investment to replace, and that are functionally necessary for the day-to-day operations of the transportation system that is owned, operated, and maintained by Caltrans District 1." The assets that fall within this category include:

- Bridges
- Stormwater Facilities
- Rest Areas
- Park & Ride Facilities
- Weigh Stations
- Traffic Signals
- Road Weather Information Systems
- Call Boxes
- Other Similar Significant Assets

Over 16,000 such assets were inventoried and analyzed based on existing data sources as part of this study. Data sufficient for analysis in this study were not available for all assets that fall within the definition above. For instance, data for regulatory signage (e.g. speed limit signs), barriers (e.g. guardrails and concrete barriers), and retaining walls was not available.

Caltrans District 1 owns and operates several types of assets that do not fall within the definition presented above. These include land holdings that serve as restoration/mitigation sites, vehicles, and roadside landscaping installed by the District. This study did not consider these types of assets that are not directly necessary for the day-to-day operations of the transportation system per the definition above.

Also incorporated into this study are analyses of the "services" provided by the above assets. Such services include: Average Daily Traffic (ADT), which indicates the average volume of vehicles that travel within a given segment of roadway', designated Bus Routes, designated Bike Routes, and other similar services. Caltrans District 1 provided GIS data for the "services" provided by the assets.

In addition, "indicators of potential needs for services" were evaluated such as the population or number of commercially-zoned parcels within a given distance of the roadway. GIS data for these indicators of potential needs for services were provided by the four Regional Transportation Planning Agencies (RPTAs) within District 1 and the four Counties within District 1. The relevant information obtained from all sources was compiled resulting in hundreds of thousands of individual data points that were evaluated in association with the services and indicators of need for service.

3.1.2 Climate Data

Projecting potential climate trends and extremes requires first establishing future scenarios of greenhouse gas (GHG) emissions that will influence future climate patterns. Due to the high level of uncertainty in the evolution of these factors, a series of qualitative storylines describing the evolution of possible trajectories of heat-trapping GHG emissions were developed by the International Panel on Climate Change (IPCC) for the IPCC Fourth Assessment Report (AR4) (IPCC 2007). These were used to guide climate change modelling efforts in AR4 upon which most of the available climate impact modelling has been based. The IPCC's (2000) special report on emissions scenarios (SRES) provides six scenario groups of plausible global emissions pathways, with no assigned probabilities of occurrence. Two of these scenarios, A2 and B1, were selected for use with this study to represent medium-high and relatively low (or "best-case") emissions projections respectively (Cayan et al. 2012). These emissions scenarios are defined as follows:

A2. Medium-high emissions resulting from continuous population growth coupled with internationally uneven economic and technological growth. Under this scenario, emissions increase through the 21st century and by 2100 atmospheric carbon dioxide (CO2) levels are approximately three-times greater than pre-industrial levels.

B1. Lower emissions than A2, resulting from a population that peaks mid-century and declines thereafter, with improving economic conditions and technological advancements leading to more efficient utilization of resources. Under this scenario, emissions peak mid-century and then decline, leading to a net atmospheric CO2 concentration approximately double that of pre-industrial levels. This scenario is often referred to as a "best-case" scenario.

General Circulation Models (GCMs)

General circulation models (GCMs) are used for predicting climate change. They model how the atmosphere, oceans, land surface, and ice interact to create weather and climate over long periods of time (decades and centuries) over the whole globe. GCMs subdivide the Earth's surface, atmosphere, and oceans into a 3D grid of thousands of cells. Standard physical equations for the transfer of heat, water, and momentum are solved for each grid cell to predict temperature, precipitation, and winds. Many relevant processes are well represented at the scale of these grid cells, such as the large-scale westerly flow of moisture from the Pacific Ocean. Due to the spread of climate projections over the various models, data is often averaged over multiple GCMs to avoid biasing towards any one model. To identify the GCMs that were best suited to predicting climate phenomena in the State of California, Cayan et al. (2012) selected six models from AR4 based on data availability and on historical skill in representing climate patterns in California, including seasonal precipitation and temperature, annual variability of precipitation, and the El Niño/Southern

Oscillation (ENSO) phenomenon. Data was obtained for six GCMs considered representative of climate trends in California. Each model has multiple runs with 16 total runs for the A2 scenario, and 17 total runs for the B1 scenario. Runs represent different initial conditions in the GCMs.

Data for a series of climate stressors downscaled to the 12-kilometer (7.5-mile) scale has been archived and made available for public use on the World Climate Research Programme's (WCRP) Coupled Model Intercomparison Project Phase 3 (CMIP3) website (http://gdo-dcp.ucllnl.org). This data has been widely applied for evaluating climate trends in California. To remain consistent with existing projection information for California the CMIP3 data was used for this study. .

Downscaling

GCMs are designed to represent climate change processes at the global scale. Models can show differences in the rate of climate change at different locations, but only on the continental scale. The size of the GCM grid cells, and thus the spatial resolution of the climate projections, is limited by the computing power necessary to solve the equations for all of the grid cells. Thus, the climate models at the time of the latest IPCC report in 2007 produced output at spatial scales of roughly 120 to 180 miles.

Particularly in mountainous regions, such as the California coastal ranges and the Sierra Nevada, this scale is too coarse to capture the many important effects of topography on climate. The scale of GCM output is also too coarse to use as input for many models predicting environmental impacts, such as basin-scale hydrologic and water system models, or wildlife habitat models. Therefore, techniques to reduce the spatial scale of the GCM output (that is, downscaling) are needed for most user applications. Data downscaling used for this project is further discussed in **Appendix 2: Climate Data Projections for Caltrans District 1 Climate Change Pilot Study**

3.1.3 Data Integration Activities

Additional data was either already in a GIS format or was converted into a format that could be used in GIS. Databases recorded location data, values, and other pertinent information. This included information pertaining to political boundaries, population, land uses, county roads, topography, water features, flood zones, erosion hazard zones, temperature, rainfall and runoff changes, etc. In this format, the data was capable of being overlaid, manipulated, and processed to generate "heat maps" to express risk and vulnerability.

3.2 Methods

The analysis methods are based on selecting assets and grouping in logical segments and selecting climate stressors that can impact segments of assets. This leads to an evaluation of the vulnerability of assets, selection of the most vulnerable assets, and identification and selection of adaptation strategies for the most vulnerable assets.

3.2.1 Selection of Assets Through Segmentation

The scope and scale of this project did not allow for an individual analysis of each of the more than 16,000 physical assets and the hundreds of thousands of data points associated with the services/ indicators. Such an analysis is not appropriate for this level of study due to the significant level of effort required to process and describe the large geographic area by its individual data points. A roadway segmentation strategy was used to group data intersecting finite length of roadway so that manageable and logical conclusions could be developed.

There are 23 Caltrans roadways within District 1. Caltrans currently utilizes several approaches of dividing these roadways into segments depending on how the information is to be used. For example, long-range planning may have a different need for segmenting roadways than day-to-day maintenance and operations. Also, roads are segmented to facilitate the collection of certain types of data. For instance, different segmentation strategies are used for evaluating Average Daily Traffic (ADT) segments, Traffic Accident Surveillance and Analysis System (TASAS), Highway Logs, maintenance districts, and Transportation Concept Report (TCR) segments. The TCR strategy is commonly associated with broader transportation needs and was therefore selected as the most appropriate segmentation strategy for evaluating and reporting the criticality of assets within the District.

Each Caltrans roadway in District 1 is described by a TCR, which is a long-range planning document that describes the current characteristics of the transportation corridor and establishes a twenty-year planning strategy. The TCRs define goals for the development of the transportation corridor in terms of level of service (LOS) and type of facilities, and broadly identifies the improvements needed to reach those goals.

There are 87 TCR segments within District 1 (herein referred to as segments): 12 in Del Norte County, 30 in Humboldt County, 28 in Mendocino County, and 17 in Lake County. TCR segments vary in length from 0.3 to 69.2 miles. Those segments greater than 25 miles in length were evaluated for sub-segmentation so that each sub-segment would better represent the location of community and highway connections as well as geographic features. Segments on Highway 101, 1 and 162 were sub-segmented resulting in a total of 93 TCR segments and subsegments.

3.2.2 Selection of Climate Stressors and Associated Analytical Activities

Increased extreme temperatures have implications for erosion and wild fire risks. Variations in rainfall can also increase runoff, which when combined with erosion, can result in landslides. Individual climate stressors and associated analytical activities are discussed below. **Appendix 2: Climate Data Projections for Caltrans District 1 Climate Change Pilot Study** discusses these issues in greater detail.

Temperature

Roads have historically and are currently challenged by climate-related events. Vulnerabilities are already present that would be exacerbated under climate change. Climate models indicated that temperatures will increase in much of the District. The annual average of daily maximum temperature for District 1 is projected to increase by approximately 4.1°F to 6.7°F by 2100.

Models suggest that there will be an increase of 3 to 3.3 extreme temperature days in the District by 2050, and 4.1 to 6.7 extreme temperature days by 2100. For this study, extreme temperature is defined as the number of days per year exceeding 95° F, referred to here as “heat days.” Evaluating the exposure of assets to temperature considered the climate scenarios that projected the greatest increase in the number of extreme heat days.

Precipitation

For this study, extreme precipitation was characterized by the 98th percentile daily precipitation event over 30-year periods for 2050 and 2100. The 2050 timeframe was estimated based on the period from 2035 to 2064; the 2100 timeframe was estimated based on the period from 2070 to 2099. The 98th percentile is a statistical measure of the extreme occurrence which may be exceeded 2% of the time over a given period. The 98th percentile is used as an indication of the extreme events for this study rather than the 100-year recurrence because of uncertainties in 100-year projections.

The District 1 average of the total annual precipitation for the ensemble average of models was compared to a selected “wet” model (PCM) and a selected “dry” model (GFDL) to illustrate the range in projections. The results of the wet model indicate an increase in the total annual precipitation of up to approximately 9% greater than the historic average (for B1 scenario at 2100), while the dry model shows a decrease of up to approximately 15% (for A2 scenario at 2100). These results indicate that careful interpretation and selection of future climate projections need to be considered when applying to assessing the vulnerability of assets as well as the selection of an appropriate emissions scenario. Although the projections of extreme precipitation show a wide range in relative change, the exposure analysis selected the dataset that shows the greatest increase in extreme daily rainfall event. The selection of the wet” model (PCM) run for the B1 emissions scenario, which results in the greatest change in extreme daily rainfall, was used as it provides a conservative approach to the analysis of exposure to potential impacts of flooding that may result from increased heavy precipitation events.

Runoff

The average percent change in total annual runoff for District 1 exhibits similar characteristics to the precipitation, in that there is a wide range in projections that show increase up to 150-200% and decrease up to 150-200%. The uncertainty is due to the different results from the several models used in the projections. The results are greatly affected by the different emissions scenarios, which project an increase in runoff by 2100 for the B1 scenario, and a decrease by 2100 for the A2 scenario. For this study, extreme runoff was characterized by the 98th percentile daily runoff event over 30-year periods for 2050 and 2100, similar to how extreme precipitation was characterized and described above. The 2050 timeframe was estimated based on the period from 2035 to 2064; the 2100 timeframe was estimated based on the period from 2070 to 2099. Similar to the extreme precipitation, extreme runoff projections varied greatly across models and emission scenarios. The greatest change in extreme daily runoff results from the “wet” model under the B1, and this was used in the potential for impact analysis.

Fire Risk

The projected fire risk data was obtained through Cal-Adapt.org. A separate set of projections of wildfire exposure for early-, mid- and late-century were provided by the California Department of Water Resources (DWR). The wildfire exposure data for mid- and late-century in District 1 indicates that fire exposure increases for most areas by 2100, particularly the inland areas of Lake and Mendocino Counties. Evaluation of the exposure of transportation assets to wildfire were accomplished using the DWR (2013) dataset, which was previously screened by DWR to consider the “worst-case” conditions resulting from the A2 and B1 emissions scenarios. Furthermore, DWR already rated the exposure of the original fire risk projections made by Krawchuk and Moritz (2012) in a semi-quantitative scale that could easily be applied to this vulnerability assessment.

Landslides

Projections of future landslide risk due to climate change are not available for the District 1 area. Existing information on the risk of deep-seated landslides is available from the California Geologic Survey (Wills et al. 2011). The study classifies deep-seated landslide susceptibility as a function of slope class and rock strength, with increasing susceptibility with slope and in weaker rocks. Much of District 1 is classified as high susceptibility to deep-seated landslides. We are not aware of any studies or date that indicates how the susceptibility may change due to climate change factors such as increased temperature and changes in precipitation. Shallow landslides, including debris flows, are highly correlated to extreme rainfall events, and may be of the most interest to Caltrans in terms of hazards related to climate change. We understand that numerical and empirical models of shallow landslide susceptibility have been developed by researchers and geologists; however we are unaware of available data for District 1. Efforts to map existing and projected shallow landslide susceptibility for District 1 should be considered as a tool to aid in future planning and design.

Sea Level Rise & Storm Flood Zones

There are multiple sources for sea level rise estimates, including studies by Northern Hydrology and Engineering on behalf of the Coastal Ecosystems Institute of Northern California (CEINC) specific to the Humboldt Bay region and NOAA. NOAA SLR Viewer data was used to assess frequent tidal inundation for existing and future conditions with sea level rise. Two inundation frequencies, daily high tide and annual high tide, based on existing mean higher high water and incremental increases, were used as approximations of sea level inundation areas along the District 1 coast.

In 2013, the California Coastal Commission published guidance to help coastal communities plan for sea level rise. This included a recommendation that regional sea level rise projections in the vicinity of Humboldt Bay and the Eel River mouth be altered to reflect tectonic conditions. The study team followed this guidance to estimate sea level rise for 2050 and 2100 in low and medium-high emission scenarios during the adaptation assessment phase of the project. Flooding within Humboldt Bay was also evaluated using data developed by the Humboldt Bay Sea Level Rise Adaptation Planning Project, which is discussed further in **Appendix 7**.

Storm flood zones were estimated for the California Coast for existing (year 2000) and future (2100) conditions that assume a sea level rise of 55-inches, in accordance with state guidance at the time (CCC 2011). This sea level rise projection also falls within the range recommended by the updated state guidance (CCC 2013). The storm flood mapping used a bathtub model approach mapping the 100-yr total water level resulting from 55-inches SLR by 2100. This is an overestimate of the 100-year flood zone in inland areas and is generally more accurate near the coast where wave run-up is occurring.

Storm surges combined with high tides and sea level rise provide an estimate for potential for impact analyses. An annual storm surge of 2 feet was selected as a conservative estimate based on review of tidal records at Point Arena, North Spit in Humboldt Bay, and at Crescent City. Other interactions between fluvial and tidal processes, including the water surface elevation of coastal lagoons, should be considered a special case and may need additional site specific evaluation.

Dune and Cliff Erosion

Dune and cliff erosion hazard areas resulting from low (0.6 meters or 24 inches by 2100) and high (1.4 meters or 55 inches by 2100) sea level rise for years 2025, 2050, and 2100 were also estimated and mapped for the California coast north of Santa Barbara. Some gaps in coverage exist in District 1: Crescent City harbor, ~11 miles of coast near the Del Norte/Humboldt County Line, and from the Mattole River to Humboldt/Mendocino County Line. A coastal erosion hazard zone represents an area where erosion (caused by coastal processes) has the potential to occur over a certain time period. This does not mean that the entire hazard zone is eroded away; rather, any area within this zone is at risk of damage due to erosion during a major storm event. A Pacific Institute study provides data that should be applied along stretches of the open coast in all available areas besides within Humboldt Bay. The conditions along the open coast are subject to large waves and elevated tides which result in flooding and erosion. Erosion hazard maps show the areas that may be impacted by increased erosion from sea level rise at years 2050 and 2100. These zones can be applied to the exposure analysis to determine if an asset is impacted or not. Similarly, existing and future (year 2100) flood zones that represent the approximate 100-year flood elevation can be used to assess the exposure of the assets to potential coastal flooding. Intermediate conditions at year 2050 can be inferred from results of the existing and future extreme conditions.

The climate exposure data described above was combined with criticality and potential for impact to develop overall vulnerability, which is discussed below.

3.2.3 Vulnerability Assessment Process

Vulnerability is defined by the Intergovernmental Panel on Climate Change (IPCC) as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes”.

Vulnerability takes into consideration criticality (including socioeconomic, operational, and health and safety importance) and potential for impact (including exposure, sensitivity, and adaptive capacity). Vulnerability was assessed by applying a criticality assessment to Caltrans road segments, estimating climate change effects, and calculating the potential for impact of climate change on road segments. **Appendix 4 Caltrans TCR Segment Vulnerability** discusses this phase of work. Criticality (**Appendix 1 Caltrans TCR Segment Criticality**) and potential for impact (**Appendix 3 Caltrans TCR Segment Potential for Impact**) were recorded as scores for each road segment; vulnerability was evaluated as a product of these scores. The criticality and potential for impact scores (each score ranging between 1 and 10) for each TCR segment were multiplied together to calculate a resulting score from 1 to 100, with a lower score reflecting lower resulting vulnerability.

Technical Advisory and Stakeholder Group members were consulted throughout this process. TAG and Stakeholders contributed their expertise and local knowledge. They ranked criticality criteria which was then normalized and used to weight scores.

Criticality

The methodology used in this assessment was based on the Federal Highway Administration (FHWA) documents “Climate Change & Extreme Weather Vulnerability Assessment Framework” (December 2012) and “Assessing Criticality in Transportation Adaptation Planning” (June 2011).” In particular, the methodology adopts the “Hybrid Approach,” which consists of analyzing both qualitative inputs (from local stakeholders) and quantitative inputs (from GIS and other data). The method also considered the approaches of the following previously completed Federal Highway Administration (FHWA) pilot projects:

- Climate Impacts Vulnerability Assessment, November 2011, Washington State Department of Transportation
- Assessing Infrastructure for Criticality in Mobile, AL: Draft Final Technical Memo, Task 1, March, 2011, US DOT Center for Climate Change and Environmental Forecasting
- Addressing Climate Change Adaptation in Regional Transportation Plans: A Guide for California MPOs and RTPAs: Final Report, February 2013, California Department of Transportation

The overall process began with an initial inventory of assets and related characteristics throughout the District, grouping the assets into logical transportation segments, and then evaluating the segments to assess criticality.

Criticality of segments was evaluated based on 40 criticality factors by evaluating raw data and then calculating a relative scaled score or Rating. The Rating is then multiplied by an importance weighting which results in a criticality score. This score was then scaled to a range of 1 to 10 based on the relative score. This final score presented the criticality of all segments on the same basis that can then be used for comparison and prioritization. A technical advisory group (TAG) and local stakeholders were engaged throughout the process. **Appendix 1** contains the technical memo and attachments for Caltrans TCR Segment Criticality.

Potential for Impact

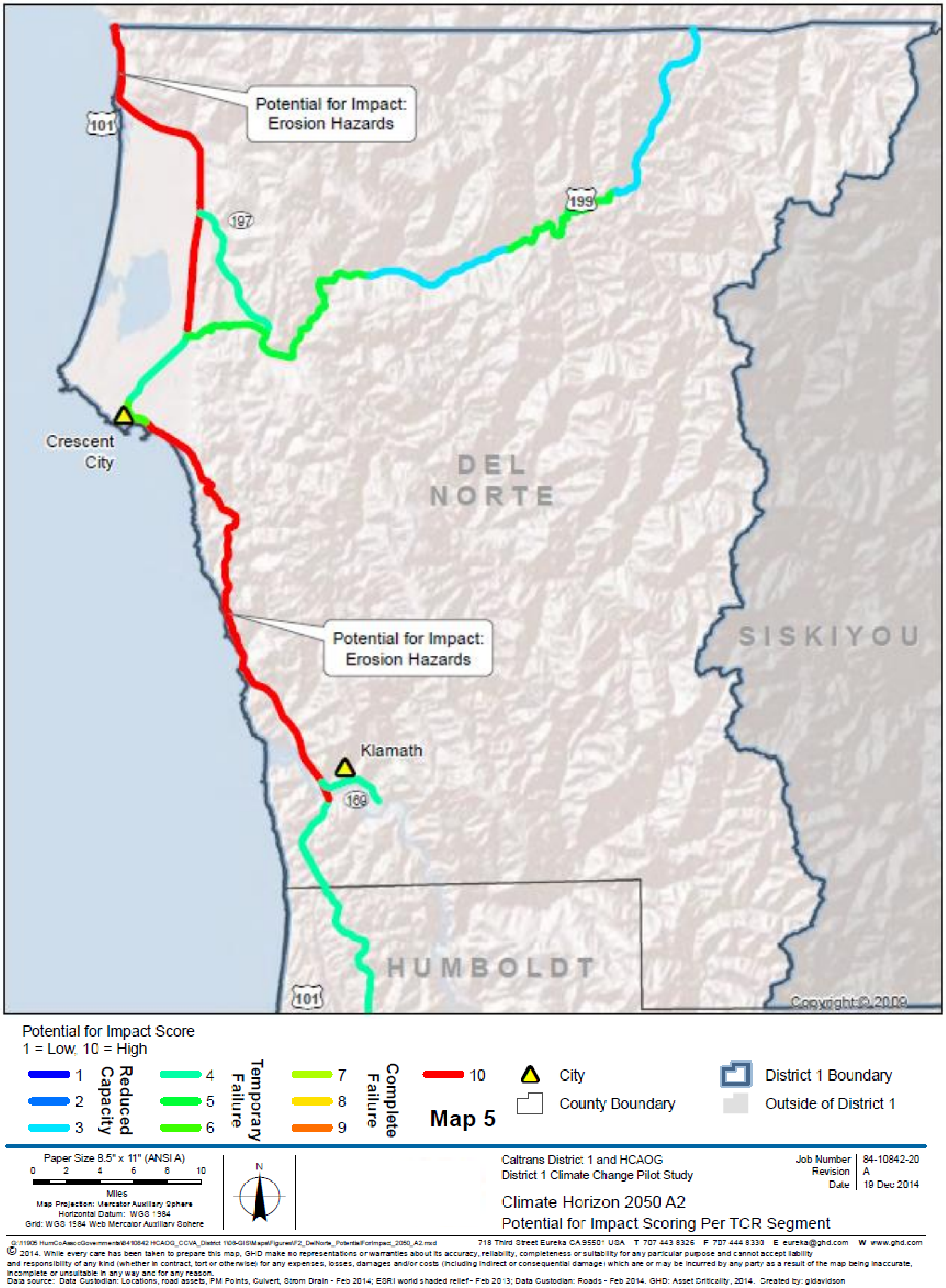
The road segments and existing assets were evaluated for the presence and magnitude of impact factors related to climate characteristics as well historical maintenance events. Exposure was analyzed using the following steps:

- Perform a spatial analysis for each TCR segment with respect to asset types, historical events, and climate impact factors;
- Quantify and extract the analysis data for potential impact scoring; and
- Score the potential impacts for each TCR segment.

Potential impact factors were scored on a scale of 0 to 10. The highest score for any single factor became the score for the segment, because any single factor can be the cause of the highest probable impact, rather than the cumulative impacts of different factors. This is much like the evaluation of sound intensity where the maximum intensity is the result of the loudest cause, not the addition of all the causes of sound. **Appendix** 3 contains the technical memo and attachments for Caltrans TCR Segment Potential for Impact. Maps 5–7 show the resultant potential for impact for the four counties in District 1. The maps include details of causes for high-ranking impact areas.

Resultant Vulnerability

As noted above, vulnerability was calculated as a product of criticality and potential for impact. The criticality and potential for impact scores (each score ranging between 1 and 10) for each TCR segment were multiplied together to calculate a resulting score up to 100, with a lower score reflecting lower vulnerability. Road segments were then ranked by vulnerability for each county. Map 8 shows the resultant final vulnerability scores for District 1.



Potential for Impact: Erosion Hazards
101
197
199
Crescent City
DEL NORTE
Potential for Impact: Erosion Hazards
SISKIYOU
Klamath
169
HUMBOLDT
101
Copyright:© 2009
Potential for Impact Score
1 = Low, 10 = High
1
2
3
Reduced Capacity
4
5
6
Temporary Failure
7
8
9
Complete Failure
10
Map 5
City
County Boundary
District 1 Boundary
Outside of District 1
Paper Size 8.5" x 11" (ANSI A)
0 2 4 6 8 10
Miles
Map Projection: Mercator Auxiliary Sphere
Horizontal Datum: WGS 1984
Grid: WGS 1984 Web Mercator Auxiliary Sphere
N
Caltrans District 1 and HCAOG
District 1 Climate Change Pilot Study
Job Number 84-10842-20
Revision A
Date 19 Dec 2014
Climate Horizon 2050 A2
Potential for Impact Scoring Per TCR Segment
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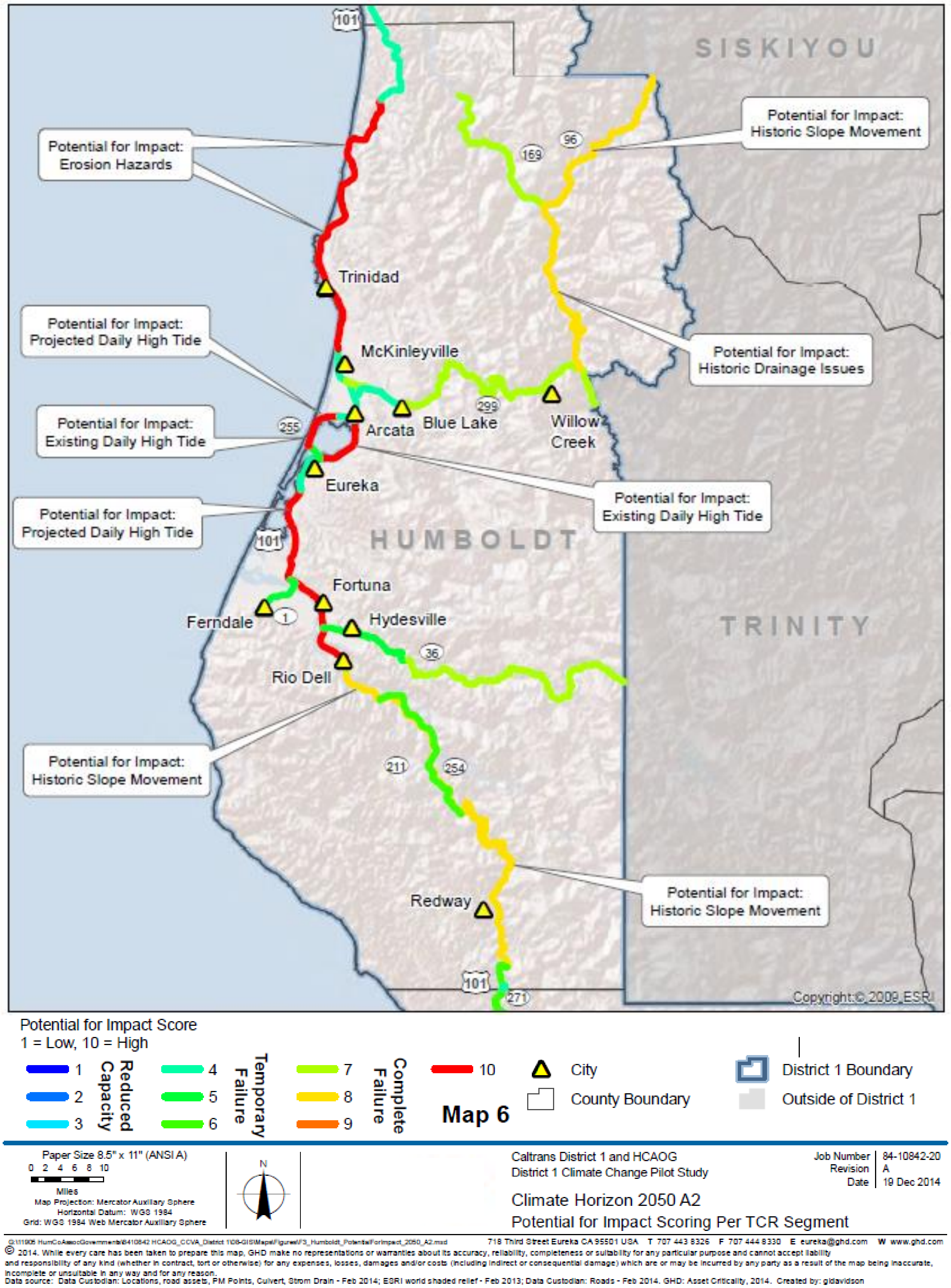
Data source: Data Custodian: Locations, road assets, PM Points, Culvert, Strom Drain - Feb 2014; ESRI world shaded relief - Feb 2013; Data Custodian: Roads - Feb 2014. GHD: Asset Criticality, 2014. Created by: gldavidson


SISKIYOU
HUMBOLDT
TRINITY
Potential for Impact: Erosion Hazards
Potential for Impact: Historic Slope Movement
Potential for Impact: Projected Daily High Tide
Potential for Impact: Historic Drainage Issues
Potential for Impact: Existing Daily High Tide
Potential for Impact: Existing Daily High Tide
Potential for Impact: Projected Daily High Tide
Potential for Impact: Historic Slope Movement
Potential for Impact: Historic Slope Movement
Trinidad
McKinleyville
Arcata
Blue Lake
Willow Creek
Eureka
Fortuna
Ferndale
Hydesville
Rio Dell
Redway
101
169
96
299
255
1
36
211
254
271
Copyright:© 2009 ESRI
Potential for Impact Score
1 = Low, 10 = High
1
2
3
Reduced Capacity
4
5
6
Temporary Failure
7
8
9
Complete Failure
10
Map 6
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County Boundary
District 1 Boundary
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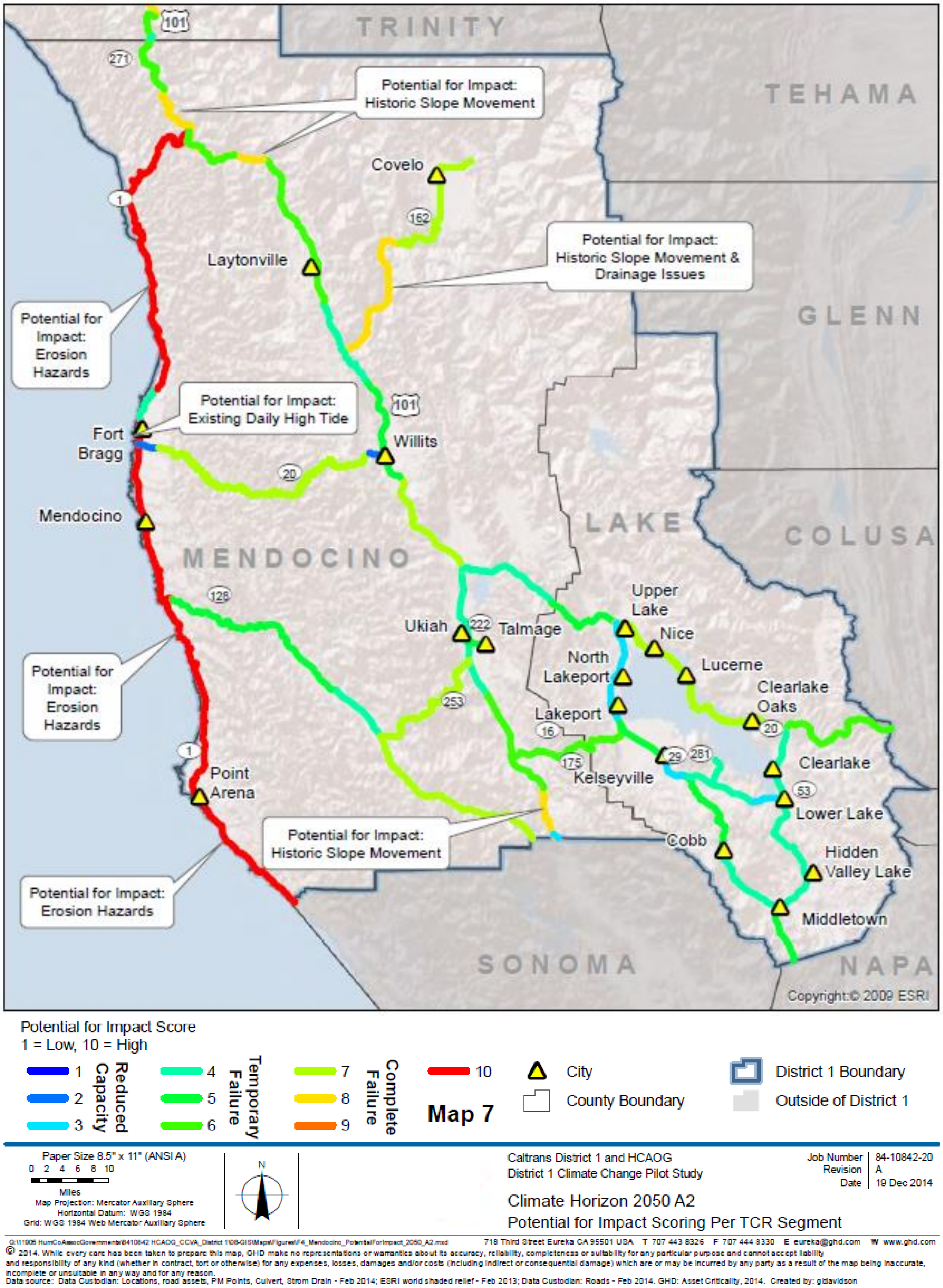

TRINITY
TEHAMA
GLENN
LAKE
COLUSA
MENDOCINO
SONOMA
NAPA
Potential for Impact: Historic Slope Movement
Potential for Impact: Historic Slope Movement & Drainage Issues
Potential for Impact: Erosion Hazards
Potential for Impact: Existing Daily High Tide
Potential for Impact: Erosion Hazards
Potential for Impact: Historic Slope Movement
Potential for Impact: Erosion Hazards
Covelo
Laytonville
Fort Bragg
Willits
Mendocino
Ukiah
Talmage
Upper Lake
Nice
North Lakeport
Lucerne
Lakeport
Clearlake Oaks
Kelseyville
Clearlake
Point Arena
Lower Lake
Cobb
Hidden Valley Lake
Middletown
101
271
1
162
20
128
222
253
16
175
29
281
53
Copyright:© 2009 ESRI
Potential for Impact Score
1 = Low, 10 = High
1
2
3
Reduced Capacity
4
5
6
Temporary Failure
7
8
9
Complete Failure
10
Map 7
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District 1 Boundary
Outside of District 1
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Overall Vulnerability Score
1 = Low, 100 = High

1-10	30.1 - 40.0	60.1 - 70.0	90.1 - 100.0	City	District 1 Boundary	
10.1 - 20.0	40.1 - 50.0	70.1 - 80.0		County Boundary	Outside of District 1	
20.1 - 30.0	50.1 - 60.0	80.1 - 90.0				

Map 8

Paper Size 8.5" x 11" (ANSI A)
0 10 20 30 40 50
Miles
Map Projection: Mercator Auxiliary Sphere
Horizontal Datum: WGS 1984
Grid: WGS 1984 Web Mercator Auxiliary Sphere

N

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Climate Horizon 2050 A2
Overall Vulnerability Scoring Per TCR Segment

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718 Third Street Eureka CA 95501 USA T 707 443 8326 F 707 444 8330 E eureka@ghd.com W www.ghd.com

Data source: Data Custodian: Locations, road assets, PM Points, Culvert, Strom Drain - Feb 2014; ESRI world shaded relief - Feb 2013; Data Custodian: Roads - Feb 2014. GHD: Asset Criticality, 2014. Created by: gldavidson

3.2.4 Selection of Vulnerable Assets for Adaptation Strategies

Figure 4 shows the distribution of vulnerability scores for District 1. The majority of the segments received low vulnerability scores: 85% received a score of lower than 50, and 95% received lower than 60.

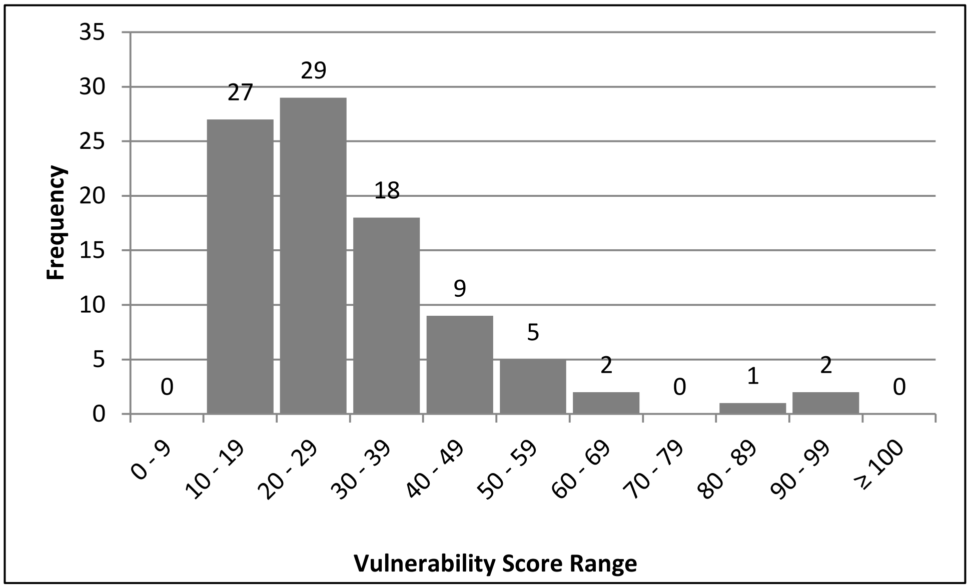

Figure 4: Frequency of Vulnerability Scores for Road Segments

This suggests that there are a relatively small number of assets that have both a high criticality and a high potential for impact and hence a high vulnerability. This means that while all assets need to be maintained to continue to meet their service objectives, the primary areas of focus are relatively few.

The following sections outline the top three most vulnerable segments in each county and highlight the key factors that contributed to each segment's vulnerability score. Changes in potential impact across the climate projections did not affect the scores for the top three most vulnerable segments in each county. Therefore, regardless of the climate change models used, the assets warranting the main attention remain the same. However, the various climate change models forecast differing levels of sea level rise, which will affect the final configuration of adaptation options that are implemented. Therefore, further work beyond this planning pilot study is needed to make final decisions on how to address climate change for these asset segments.

Del Norte County

US 101 Segment 19

The segment that was rated most vulnerable in Del Norte County is US 101 Segment 19 between Wilson Creek and south of Crescent City, which received a vulnerability score of 64. The segment received a criticality score of 6.4 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score included low redundancy, higher route classifications, and presence of traffic operating systems. The potential impact score is due to a portion of the segment being within an erosion hazard zone. This particular location is referred to as Last Chance Grade and has historically been exposed to frequent slope failure and erosion issues.

US 101 Segment 18

The segment that was rated second most vulnerable in Del Norte County is US 101 Segment 18 in the Del Norte Redwoods State Park area, which received a vulnerability score of 58. The segment received a criticality score of 5.8 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score included its lack of redundancy, presence of bridges, and higher route classifications. The potential impact factor was that the segment contains a portion of the roadway within the erosion hazard zone.

US 101 Segment 22

The segment that was rated third most vulnerable in Del Norte County is US 101 Segment 22 between the junction with US 199 and the Oregon border, which received a vulnerability score of 57. The segment received a criticality score of 5.7 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score included its high route classification and moderate redundancy. The potential impact factor was that the segment contains a portion of the roadway within the erosion hazard zone.

Humboldt County

US 101 Segment 11.3

The segment that was rated most vulnerable in Humboldt County is US 101 Segment 11.3 between Rio Dell and the south Eureka urban boundary, which received a vulnerability score of 94. The segment received a criticality score of 9.4 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score included its number of bridges, length, low redundancy, relatively high ADT, and high route classifications. The potential impact factor was the segment’s coastal proximity with portions of low elevation that has the potential for tidal inundation.

US 101 Segment 13

The segment that was rated second most vulnerable in Humboldt County is US 101 Segment 13 in Humboldt County between the north Eureka city limits and the junction with Route 255 (South Arcata), which received a vulnerability score of 77. The segment received a criticality score of 7.7 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score included high ADT, large population, high number of municipal non-park parcels, and route classifications. The potential impact factor was the segment’s coastal proximity with low elevation that has the potential for tidal inundation.

US 101 Segment 11.1

The segment that was rated third most vulnerable in Humboldt County is US 101 Segment 11.1 in Humboldt County between Richardson Grove and Weott, which received a vulnerability score of 62. The segment received a criticality score of 7.8 and a potential impact score of 8. The criticality factors that contributed to the high vulnerability score included low redundancy, presence of bridges over water, high number of stormwater facilities, presence of critical nodes, and high route classifications. The potential impact factor was the segment's frequent historical slope movement due to drainage issues.

Lake County

SR 20 Segment 6

The segment that was rated most vulnerable in Lake County is SR 20 Segment 6 between junctions with SR 29 and SR 53, which received a vulnerability score of 50. The segment received a criticality score of 7.2 and a potential impact score of 7. The criticality factors that contributed to the high vulnerability score included low level of redundancy, high number of stormwater and maintenance facilities, proximity to commercial and residential parcels, and high route classifications. The potential impact factor was the frequent and high-cost historical slope movement events, as well as chronic drainage issues.

SR 20 Segment 7

The segment that was rated second most vulnerable in Lake County is SR 20 Segment 7 between the junction with SR 53 and the Lake/Colusa County line, which received a vulnerability score of 31. The segment received a criticality score of 5.1 and a potential impact score of 6. The criticality factors that contributed to the high vulnerability score included its moderately low level of redundancy and high route classification. The potential impact factor was the frequent and high cost historical slope movement events.

SR 29 Segment 6

The segment that was rated third most vulnerable in Lake County is SR 29 Segment 6 between Kelseyville and 0.5 miles south of Lakeport (intersection with SR 175), which received a vulnerability score of 29. The segment received a criticality score of 5.9 and a potential impact score of 5. The criticality factors that contributed to the high vulnerability score included high route classification and the number of critical nodes present. The potential impact factor was exposure to frequent historical slope movement, drainage, and erosion events.

Mendocino County

SR 1 Segment 4

The segment that was rated most vulnerable in Mendocino County is SR 1 Segment 4 between the northern and southern city limits of Fort Bragg, which received a vulnerability score of 67. The segment received a criticality score of 6.7 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score included lack of significant redundancy, moderate ADT, presence of maintenance facilities, and high route classifications. The potential impact factor was the potential for inundation from the daily high tide due to sea level rise in 2050 related to the segment's low elevation at the mouth of Pudding Creek near the coast.

SR 1 Segment 3

The segment that was rated second most vulnerable in Mendocino County is SR 1 Segment 3 between Little River and the southern Fort Bragg city limit, which received a vulnerability score of 58. The segment received a criticality score of 5.8 and a potential impact score of 10. The criticality factors that contributed to the high vulnerability score include a lack of redundancy, moderate ADT, higher number of bridges, and designation as a bus route. The potential impact factor was that the segment contains both a portion of the roadway and a bridge that is within the erosion hazard zone.

US 101 Segment 7

The segment that was rated third most vulnerable in Mendocino County is US 101 Segment 7 between Bell Springs Road and the junction with SR 1 at Leggett, which received a vulnerability score of 58. The segment received a criticality score of 7.2 and a potential impact score of 8. The criticality factors that contributed to the high vulnerability score included very low level of redundancy, road length, and high number of critical nodes. The potential impact factor was frequent and high-cost historical slope movement events.

Discussion

Vulnerability scores throughout the District varied by geographic location. Coastal segments were among the most vulnerable due to the high potential impact associated with rising sea levels. Vulnerability associated with significant historical slope instability, drainage and erosion issues exist throughout the district. Routes with higher asset criticality such as lacking redundancy, high use, high route classification, and critical nodes were present throughout the District.

Each county has varying climate exposure risk and asset criticality due to geographic location, projected changes in climate, historical issues and infrastructure or assets required for continued service. Vulnerability is discussed in detail in **Appendix 4: Caltrans TCR Segment Vulnerability**.

The following four representative prototype sites were selected with one in each of the four counties in Caltrans District 1:

- Del Norte County, Hwy 101 Segment 19, from Post Mile 14.2 to 15.6, also known as Last Chance Grade.
- Humboldt County, Hwy 101 Segment 13, from Post Mile 79.3R to 85.3.
- Lake County, Hwy 20 Segment 6, from Post Miles 52.5 to R47.9 and CR 407(Nice-Lucerne Cut off).
- Mendocino County, Hwy 1 Segment 1.1 from Post Mile 17.5 to 18.6.

3.2.5 Identifying, Assessing, and Selecting Preferred Adaptation Strategies

Adaptation options were identified and evaluated based on a number of factors including cost, effectiveness, flexibility, benefits, and social and environmental factors based on the overall flow chart presented in Figure 5. The process began with a range of potential adaptation options. An evaluation and prioritization process narrowed the options to help focus future evaluation and selection processes.

When considering adaptation options, it is important to understand that climate change is a long term phenomenon with a multitude of short and long term effects. Appropriate adaptations need to be implemented within a timeframe that provides protection when it is needed. An adaptation option should be initiated based on a forecasted trigger condition such as a particular sea level elevation. In some cases, the trigger condition could occur decades in the future and so the evaluation, selection, and implementation of the most appropriate solution should be based on information that is most relevant and up to date.

Specific sites were evaluated for physical and climate factors; a range of adaptation options developed; and criteria for preliminary evaluation were considered. This process was formalized within a spreadsheet, producing a range of options with scores based upon weighted criteria. The spreadsheet became a tool to automate evaluation and ranking of the adaptation process.

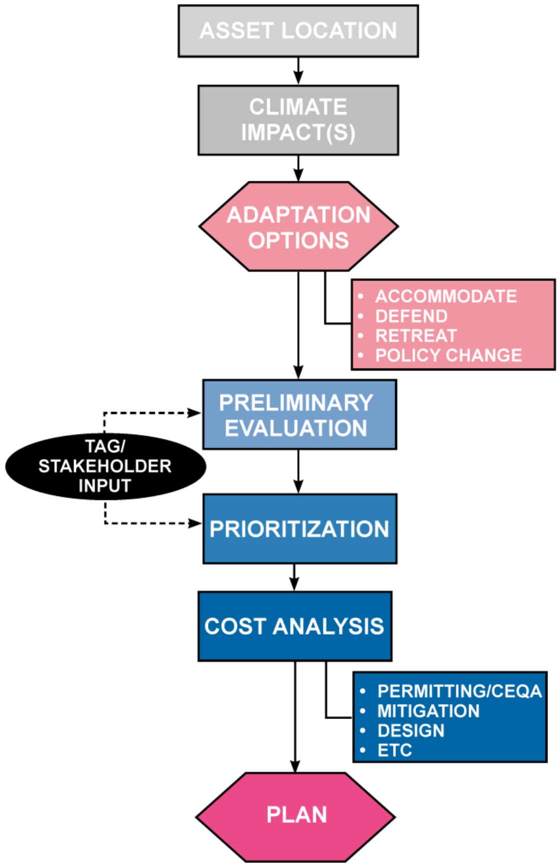

Figure 5: Adaptation Process Flowchart

Development of the adaptation methodology began with an assessment of categories of climate change impacts, primary climate factors, and secondary climate change factors. The Primary Effect of climate change factors indicates the potential large scale impacts to an asset. Secondary factors are the ways in which the primary climate factors could damage assets. They describe specific hazards that may befall a structure, such as damage due to flood, fire, or erosion. Existing protection measures, such as levees or drainage structures, may currently mute the magnitude of these impacts. Other site conditions, such as local geology, could exacerbate the magnitude. Objectives to address these secondary factors were drafted to identify overarching approaches to address secondary factors. Each objective could have multiple adaptation options. The same objective may also apply to multiple secondary effects.

Adaptation options represent a spectrum of approaches to meet the challenge of climate change, characterized as “defend, accommodate, retreat (both planned and forced), and forced retreat.” Options that “defend” an asset increase protection around the asset. Options that “accommodate” modify the asset to allow the impact to pass through the system without harming it. A typical example of an “accommodate” strategy is installation of a causeway that allows floodwaters to pass beneath a coastal road. Planned retreat strategies relocate an asset that is in a hazard zone, allowing any hazardous events to occur without trying to manage them. Forced retreat is the consequence of taking no action. This can be a deliberate strategy while other strategies are in preparation, or can be the result of no or poor planning. The category “changes in policies or practices” was also added to represent the range of maintenance, planning, or regulatory changes that can improve management of assets under climate change threats. This “defend-accommodate-retreat" framework was helpful in thinking through options that represented a range of solutions, but is not itself significant to the adaptation project selection process.

Criteria for evaluating the adaptation options involved project finances, timelines, performance, and consequences of a project. These criteria were based upon a review of prior climate change adaptation studies, and project team discussions.

These criteria were weighted using a pairwise analysis to reflect local priorities and values. Adaptation criteria were ranked for potential weighting through Stakeholder and public meetings. Stakeholders were asked to prioritize criteria. At public meetings, participants were given three stickers to use for voting in any combination on their preferred criteria. The opinion on criteria ranking was explored to understand how community and stakeholder values and priorities could be translated into the tool. Final weighting of criteria are presented in the next section.

Developing thresholds for project selection and implementation timing was also incorporated into the model. The relative design life of adaptation options was programmed into the spreadsheets, allowing users to iteratively explore how different options may be desirable for different climate change projections, target design thresholds for expensive projects with long design lives, or identify maintenance triggers for upscaling to more expensive adaptation options.

For example, a bridge may have a design life of 80-100 years, but could be become redundant in less time by climate change factors. In such a scenario, managers may choose to maintain existing assets for an extended period ("defend" scenario) while planning for replacement of the asset as climate impacts are better documented and projections are more accurate, or managers may choose to design the project according to current projections for the worst case scenario in 2100.

The process creates a way to rapidly winnow a large field of potential adaptation options to a more manageable list. It is not a substitute for the balancing of technical, sociological, ecological, and political decisions that must be made through dialogue, but a means of refining priorities.

Adaptation Option Selection

Many adaptation options can be considered for every climate change event and situation and the overall proves for selecting options is presented in Figure 6. The intent of the tool developed in this study is not to capture every possibility, but to identify a variety of general options ranging from the "no project" approach to relocation, protection, or reconstruction.

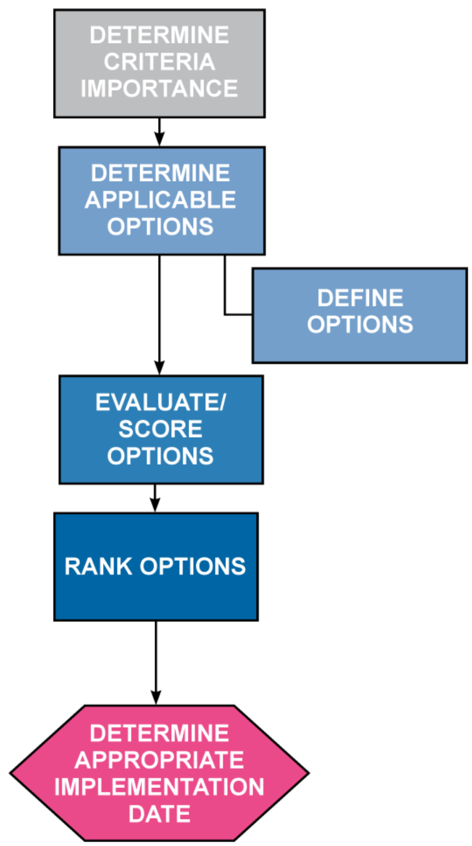

Figure 6: Adaptation Evaluation and Prioritization Flowchart

Nine primary adaptation options are included within the adaptation tool. These adaptation options were developed through an evaluation of climate impacts, primary and secondary effects, and climate change objectives. The final list represents primary types of climate adaptation projects. The adaptation tool provides specific examples of adaptation options that fall within each primary category.

Once the primary adaptation options are chosen, the adaptation tool automatically carries over those options into a scoring sheet and a more detailed description is entered in the adaptation tool. The more detailed description is developed based on a review of the example adaptations and site specific characteristics.

The preliminary evaluation process is intended to objectively compare a number of adaptation options based on a list of predetermined assessment criteria. The process begins by determining the appropriate assessment criteria and the level of each criterion's importance. When compared against one another, the criterion is weighted. A higher weight represents greater relative importance. Next, options that were pre-selected through the prior steps are then evaluated (numerically scored) based on each assessment criterion. The total weighted score for each option is calculated. Estimating the timeframe for each option is then performed to identify the impacts of different implementation dates.

Assessment Criteria

Seven (7) different criteria were selected to independently score each option:

1. Total Capital Investment
2. Average Annual Cost
3. Usable Life
4. Level of Performance
5. Flexibility
6. Environmental Considerations
7. Social Considerations

Factors relating to cost, effectiveness, flexibility, benefits and impacts were considered and then weighted based on importance level. The criteria are defined specifically to relate to the climate change impacts and terminology used in this study. Each criterion is given a numerical range of scores to choose from. The assessment criteria are weighted with respect to one another and used to emphasize importance of one or more criteria. Input on the level of importance was obtained from TAG and Stakeholder feedback as well as the public.

The choices for adaptation options are relatively general in nature. Prior to evaluation of each option, a conceptual plan must be considered. Information such as the limits of work, level of protection, materials used, etc. must be described and used when evaluating the options. For example, an appropriate description might be to, "*Create a living shoreline averaging 350' long by 40' wide with an oyster reef breakwater, vegetative salt marsh and riparian buffer.*" If this option is chosen and implemented, a significant amount of additional detail will be necessary for the design and construction; however, for planning purposes only the basic configuration need be entered. The description of the conceptual plan should be entered into the "Enter Description or Comment" box.

Public Consultation

Public meetings were scheduled for early in the adaptation assessment process. Meetings were planned in each county, and local media contacted. With the exception of Mendocino County, all the meeting sites were relatively close to the adaptation pilot project sites. In Mendocino, the meeting site was about one hour away. This was due to there being a larger population in Fort Bragg than Point Arena. The meetings provided a briefing on local climate change projections, and the regional vulnerability assessment effort. It then focused on the kinds of impacts on transportation systems climate change would bring, and proposed a range of adaptation options for prototype sites. Criteria for assessing adaptation options were also discussed. The public was then invited to provide verbal and written feedback. The adaptation options and criteria were posted around the room in a gallery format. Stickers were used to express preferences for options, and markers were available for written comment. Adaptation criteria votes were combined with feedback from Stakeholders and TAG members to weight criteria in the adaptation option evaluation phase. The public meetings are documented in **Appendix 10: Stakeholder and Public Meeting Summar**y.

Adaptation Option Evaluation

Once the adaptation options are entered and the description completed, the assessment criteria are scored. The first two assessment criteria are based on information input by the user for Design Service Life and Total Capital Investment cost. The Design Service Life can vary depending on the infrastructure, but essentially it is the “life” of the infrastructure until major deterioration begins to

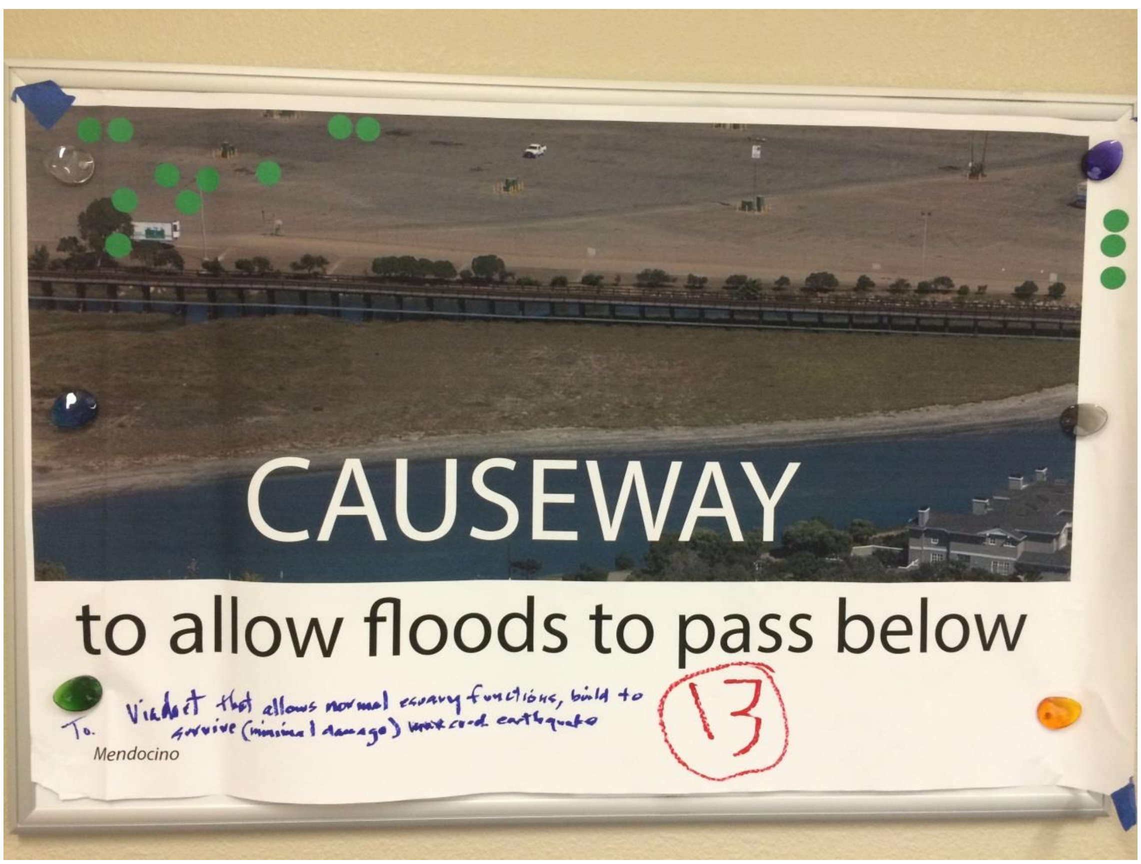

Figure 7: Causeway Adaptation Option with Votes and Comments from the Mendocino County Public Meeting

occur. For the purposes of the study, the design service life of a roadway assumes that regular, routine maintenance occurs (e.g. overlays, crack sealing, etc.). The Total Capital Investment is based on the estimated cost for full implementation of the option (from planning through construction). Based on the information provided, the first two criteria (Total Capital Investment and Average Annual Cost) are automatically calculated and scored. The remaining criteria require input based on the conditions of the location and/or the option being evaluated. When evaluating the option, the definition of each criterion should be reviewed and used to consider the appropriate scoring of the option. When all of the criteria have been scored, the weighted score is calculated and displayed under "Total Score."

Adaptation is discussed in detail in **Appendices 5–9**.

4. Findings

4.1 Key Conclusions

Climate change will predominately impact District 1 roads through sea level rise and increased coastal erosion hazards. Inland roads will tend to be more affected by increased precipitation related hazards, although sea level rise can affect inland roads through backwater effects on rivers. Preparing for these climate change driven events will require further planning and evaluation to select the best approaches to be implemented at the most opportune time. The tools and the work completed for the prototype site provides a process and an initial foundation for further work.

Existing hazards such as inland erosion, landslides, and fire will still exist and may increase with climate change, but this type of impact is already being addressed with maintenance and replacement strategies. Since non-coastal climate change effects typically are not as dramatic, appropriate adaptation strategies are more geared to monitoring and maintenance, updates to standards for design storm events, and changes in materials and construction methods to better prepare for potentially more intense climatic conditions.

Through the timeline and implementation tool, this study demonstrated that regardless of the adaptation option selected, advance planning including environmental permitting is critical to being prepared to adapt to the effects of climate change.

The projected rate of sea level rise and the associated effects on the natural environment, private property, and developed infrastructure suggests that greater collaboration will be needed between permitting authorities and project proponents to create workable solutions.

Workable solutions also require the engagement of a multitude of stakeholders because there may be a multitude of interests affected by climate change in an area. There may need to be collaborative solutions between public entities, businesses and private parties, as there are multiple property owners in most areas that will need to collaborate on the mutual protection of public and private assets. The process of engagement should be started early and the broad spectrum of effects and adaptations should be considered so that robust long term solutions can be developed.

4.2 Characterization of Vulnerabilities and Risks

Caltrans District 1 is a rugged, sporadically developed landscape characterized by mountainous topography, winding roads, and relatively low population densities. The Humboldt Bay-lower Eel River Valley is the largest population cluster, followed by Ukiah. Other communities are sparsely populated with little or no road redundancy. The diverse topography and natural features are fraught with instabilities that will be exacerbated by climate change.

Climate change is predicted to increase temperatures, which will alter habitats and likely trigger increases in erosion, landslides, and wild fires. Rainfall patterns are expected to change, and sea levels will rise.

The small communities of District 1 risk extended periods of isolation and lack of access to emergency services due to climate change impacts on the road system. While the vulnerability assessment captured the role of population in elevating road segments in the ranking, it was evident that less populated areas would also be vulnerable. Selected road segments reflect a range of conditions, including potentially impacted small communities.

4.2.1 Hwy 101 at Last Chance Grade, Del Norte County

Highway 101 is the primary connector of Crescent City to other destinations in California. As such, it is critical to the economy and well-being of residents. For goods and services movement along the West Coast, it is also an important route, with Interstate 5 an approximately 4 or 5 hour drive to the east.

Highway 101 at Last Chance Grade demonstrates how managing an existing geologic hazards (in this case, a slow-moving earthflow), can be exacerbated by climate change effects. Gullying and landward bluff erosion increase hazards and management issues. Sea level rise is predicted to

Figure 8: Gully Erosion at Last Chance Grade, Del Norte County

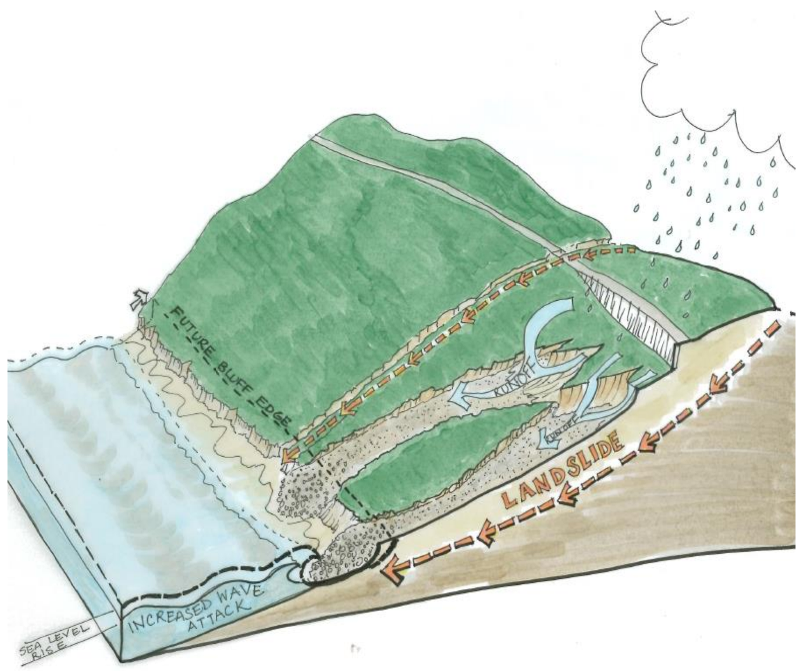

Figure 9: Diagram of Processes Affecting Last Chance Grade, Del Norte County

increase by up to 19 inches by 2050, and up to 56 inches by 2100. Precipitation may increase by up to 9% by 2050, and 16% by 2100.

Under such circumstances, it is reasonable to predict increased wave attack at the bluff, and increased gully erosion (rock and debris slides, and debris flows) in the future.

This site is currently monitored for signs of land movement. Reconstruction and maintenance of retaining and soil nail walls has been a costly endeavour for the District.

4.2.2 Highway 1, Garcia River, Mendocino County

The Garcia River mouth and a tributary, Hathaway Creek, meet in the floodplain through which Highway 1 crosses, just north of Point Arena in Mendocino County. Residents of Point Arena live on the south side of the river, while schools and some employers are on the north side. During floods, the bridge itself is unlikely to flood. However, flood waters will occupy low-lying reaches of road. Where Highway 1 crosses Hathaway Creek, it can take several days for flood waters to recede. A stream gage upstream is monitored for rising water levels; when a flood is expected, community members have about one hour to retreat to the side of the river where they live. In order to prevent stranding, children are pulled out of school and bussed home early in these situations. Such a condition can also pose challenges for emergency services delivery.

Climate change is expected to increase sea level rise by up to 24 inches by 2050 and 66 inches by 2100. Precipitation may increase by up to 4% by 2050 and 11% by 2100. Extreme runoff may increase by up to 10.8% by 2050, and 15.8% by 2100. Existing flood issues on Highway 1 are likely to increase.

Figure 10: Hathaway Creek at Highway 1, Looking Downstream. Photo: Craig Bell, via krisweb.com

These flood conditions are experienced at several other coastal river mouths in Mendocino County.

4.2.3 Highway 20 and County Road 407 at Middle Creek/Rodman Slough, Lake County

Clear Lake is the largest natural freshwater lake entirely within the state of California. Numerous drainages feed the lake. Some of these are diked to protect former areas of the lake that were reclaimed for agriculture. These dikes are undersized for all but the smallest storms, and are frequently overtopped. Small communities also line the perimeter of the lake, particularly along Highway 20. Rainfall causes the lake to rise, backing up into drainages. Roads can therefore be impacted by flooding from both directions: drainage moving downstream and lake backwatering. While downstream peak flows normally pass fairly quickly, backwatering can take weeks to recede. Most communities lining the lake have an alternate route, including Highway 29. However, winding and narrow county roads may make access to these alternates risky in storm conditions.

Additionally, Lake County is working with the Army Corps of Engineers and local stakeholders to restore portions of Middle Creek and Rodman Slough, and has begun property acquisition to this end. The project intends to breach dikes and restore wetland and floodplain functions in the former lake footprint. This has the potential to increase flooding on Highway 20 and County Road 407.

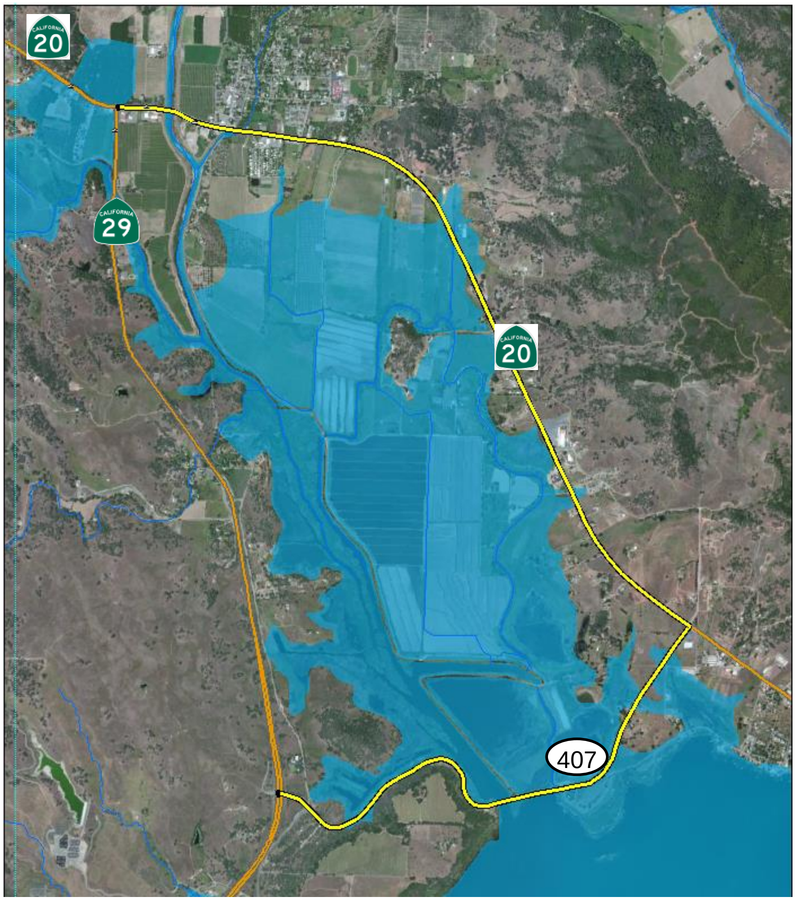

Figure 11: 100-year FEMA Floodplain at Middle Creek/Rodman Slough Demonstrates Potential Loss of Access to Highway 29, an Alternate Route Along Clear Lake, Under Flood Conditions.

In Lake County, climate change planning using the "wet" model predicts increases in precipitation by up to 10% by 2050 and by up to 12% by 2100. There is considerable variability to extreme runoff predictions, ranging from 6-51% by 2050 and 6 to 69% by 2100 relative to runoff rates from 1970 to 2000. These increases are expected to exacerbate flooding along Clear Lake, and reduce the viability of alternate routes in the future.

These segments serve smaller communities in rural agricultural and natural settings. Due to the small population sizes, criticality rankings on the whole were lower for them. This influenced the overall vulnerability rankings, with a dampening effect on scores relative to more populated areas. Small communities throughout the District risk extended periods of isolation and limited access to emergency services. Despite the scores, the Project Team recognized the importance of exploring adaptation at these highly representative sites.

4.2.4 Highway 101 Eureka- Arcata Corridor, Humboldt County

With a larger population, Humboldt Bay-Lower Eel River Valley scored highest in the vulnerability ranking. Disruptions to Highway 101 will interrupt service for a relatively greater number of people; some segments of Highway 101, such as the bridge over the Eel River, lack redundancy and therefore could also isolate many people for an extended period of time. Humboldt Bay was diked in the late 1800s to reclaim land for agricultural uses. The state of maintenance of these dikes varies widely, as they are managed in reaches by individual property owners. There is no larger assessment district or managing body for dike system. A recent breach in a dike brought tide waters very close to Highway 101 south of Eureka in 2014. An inflatable dam/water bag was placed in the dike as an emergency measure. The reach of Highway 101 between Eureka and Arcata, is mainly protected by the elevated railroad grade. Areas of this railroad grade are in disrepair. Other dikes along sloughs also provide flood protection for this reach.

Climate change is expected to increase sea levels in Humboldt Bay by a high end estimate of up to 26 inches by 2050 and up to 70 inches by 2100. Precipitation is predicted to increase by up to 11% by 2050 and up to 14% by 2100, with estimated extreme runoff increases by up to 9% by 2050 and 12% by 2100. Figure 12 below the predicted water heights in year 2100 under the high GHG emission scenario and the annual average King tide.

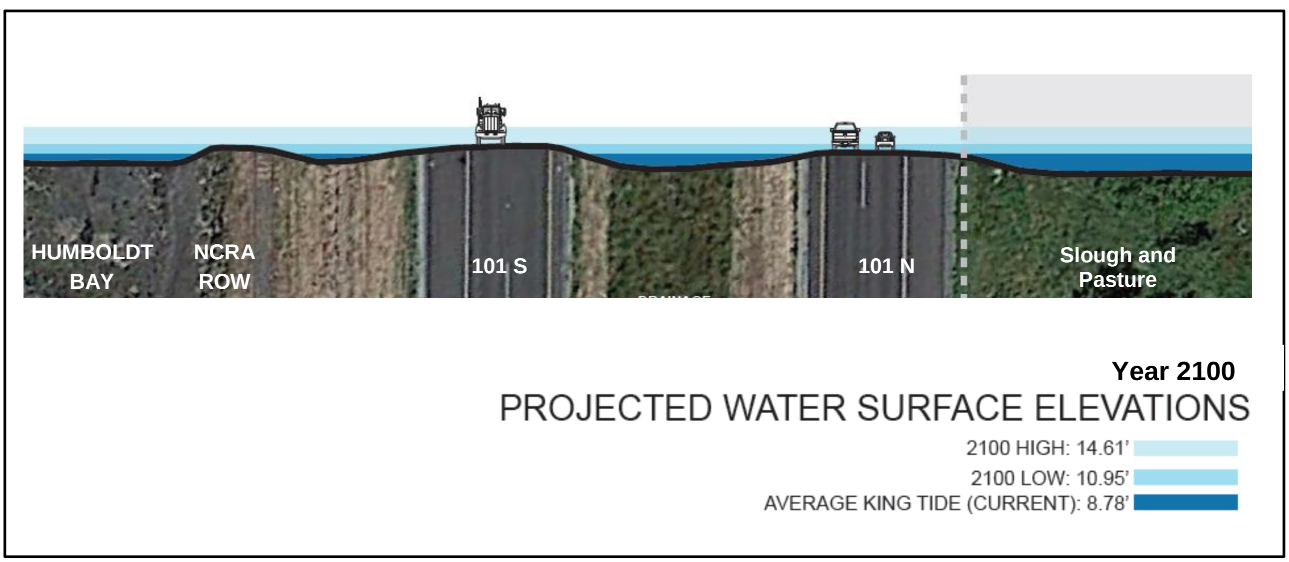

Figure 12: Vulnerability of Highway 101 to Sea Level Rise Along Humboldt Bay

Much of Highway 101 along Humboldt Bay is only a few feet above the current, average height of King Tides, a twice-yearly extreme tide event. Extreme weather has caused flooding in the highway in the past. It is expected that without management of the dike system, the bay will reclaim its historical footprint, flooding currently reclaimed agricultural lands and some developed areas. Modeling has shown that the southern reach of the project study location will be regularly inundated by 2050, and that by 2100, almost the entire six miles will be under water. These model estimates considered mean monthly maximum water (MMMW) and average King Tide conditions. Should a 100-year storm or other extreme storm event occur, the estimated elevations will be even higher. Dike breaches will also accelerate the occurrence of flooding in the region.

4.2.5 Summary of Vulnerability

The final potential for impact and vulnerability maps are presented in this section.

Caltrans District 1 is faced with many challenges to prepare for climate change. While it may lack the population of other areas of California, providing adequate service to the many small communities it serves requires resourcefulness and dedication in distributing its limited funding and manpower. Climate change elevates these tough decisions.

4.3 Findings from Analysis of Adaptation Strategies

Adaptation options responsive to climate change effects were explored for four prototype locations. **Appendix 5: Caltrans Asset Adaptation Assessment Methodology** presents the overall adaptation evaluation methodology. Appendices 6 through 9 describe the conceptual design process, cost estimation, and other considerations as follows for each prototype site:

- Appendix 6, Caltrans Asset Adaptation Assessment, Del Norte County Prototype Location;
- Appendix 7, Caltrans Asset Adaptation Assessment, Humboldt County Prototype Location;
- Appendix 8, Caltrans Asset Adaptation Assessment, Lake County Prototype Location;
- Appendix 9, Caltrans Asset Adaptation Assessment, Mendocino County Prototype Location;

This section provides examples of the analyses and findings for all viable options at each location. The examples provided do not indicate a preference on the part of the study authors; they are meant to be illustrative of the range of options considered, and demonstrate how the tool applied analytic criteria to different situations.

Adaptation options were independently scored against seven assessment criteria, which are described below. Each criteria was weighted based on input from the TAG, stakeholders, and the public and the score for each criteria multiple by the weight and summed for a total score. The weight of each criteria is included below as well. The score for adaptation options evaluated are included in the sections below.

- Total Capital Investment: The estimated total cost of implementation of the adaptation option including, but not limited to the costs associated with planning, permitting, design and construction (weight = 3.7)
- Average Annual Cost: The total capital investment cost of implementing the adaptation option with respect to the design service life (weight = 11.1)
- Usable Life: The comparison of the adaptation option's design service life, with respect to the climate change event horizon (weight = 18.5)
- Level of Performance: The existing level of protection compared to the anticipated level of protection, at the specified climate change event horizon (weight = 25.9)
- Flexibility: The ability of the adaptation option (at any stage in development) to be modified to provide a higher level of protection against impacts or to be updated as new data models for climate change are developed. Flexibility also considers the potential for the adaptation option to be phased or completed in segments over a longer period of time. The benefit to phasing (for the purposes of scoring this criterion) is that the total capital investment cost can be distributed over a period of many years (weight = 7.4)
- Environmental Considerations: The potential of the adaptation option to improve or impact the existing environmental conditions with respect to integrity, diversity, or abundance of the natural ecosystem's functions and/or habitat (weight = 14.8)
- Social Considerations: the potential of the adaptation option to improve or impact the communities social welfare (weight = 18.5)

Del Norte County

Four adaptation options were proposed for consideration; three were potentially feasible and were explored using the adaptation tool developed for this project. Below is an example of the summary of findings produced by using the adaptation tool. This example is for Option 2: Relocate infrastructure.

Table 2: Last Chance Grade Example Scoring Sheet for Adaptation Option 2: Relocate Infrastructure

Assessment Criteria	Value	Comments
Assumed Design Service Life	100 years	High end of the design life of a concrete structure. Assumed structure is properly maintained to protect integrity
Assumed Total Capital Investment	$ 300 Million to $1 Billion	Cost range estimated from on-going Caltrans feasibility study
Usable Life	3: Surpasses	The usable life is beyond the 2100 scenario, thus, the option surpasses the climate horizon in its useful life
Level of Performance	3: Enhanced	This option provides enhanced protection of the asset in comparison with the existing condition
Flexibility	0: None	This option would not be flexible once constructed. It could not be relocated
Environmental Considerations	-3: Significant net impact	It is assumed that significant disturbance to the Redwood National and State Park would occur and there is the potential for disturbance of cultural sites.
Social Considerations	3: Significant net improvement	It is assumed this option can feasibly address the landslide/erosion issues and would keep the highway open, providing a significant social improvement.

Table 3 ranks and summarizes the options and the score for the 2050 climate scenario:

Table 3: Summary of Del Norte County Prototype Location Adaptation Options

Rank	Adaptation Option	Project Description	Score 2050	Order of Magnitude Cost Estimate
1	Provide major structural protection	Provide a high technology solution approximately within the existing road right of way, possibly including retaining walls, minor re-alignments, and bridges or tunnels	148 to 163	$1 billion or more
2	Relocate infrastructure (horizontally)	Construct a full bypass	144	$ 300 million to $1 billion
3	Increase the infrastructure's maintenance and inspection interval and continue to monitor/evaluate	Equivalent to the No project alternative. Only temporary measures enacted and repairs made on an as needed basis. Includes cumulative average annual repair costs for 20 years and assumes appropriate signage for road restrictions added	-33	$ 26,500,000 (20 –year present worth of estimated annual maintenance costs)

Humboldt County

Eight adaptation options were proposed for consideration to address sea level rise along Highway 101 on Humboldt Bay. These strategies include increased armouring/flood walls, elevated infrastructure, and relocated structures. Figure 13 shows the adaptation options for Humboldt Bay. Additional figures can be found in **Appendix 7, Caltrans Asset Adaptation Assessment, Humboldt County Prototype Location**.

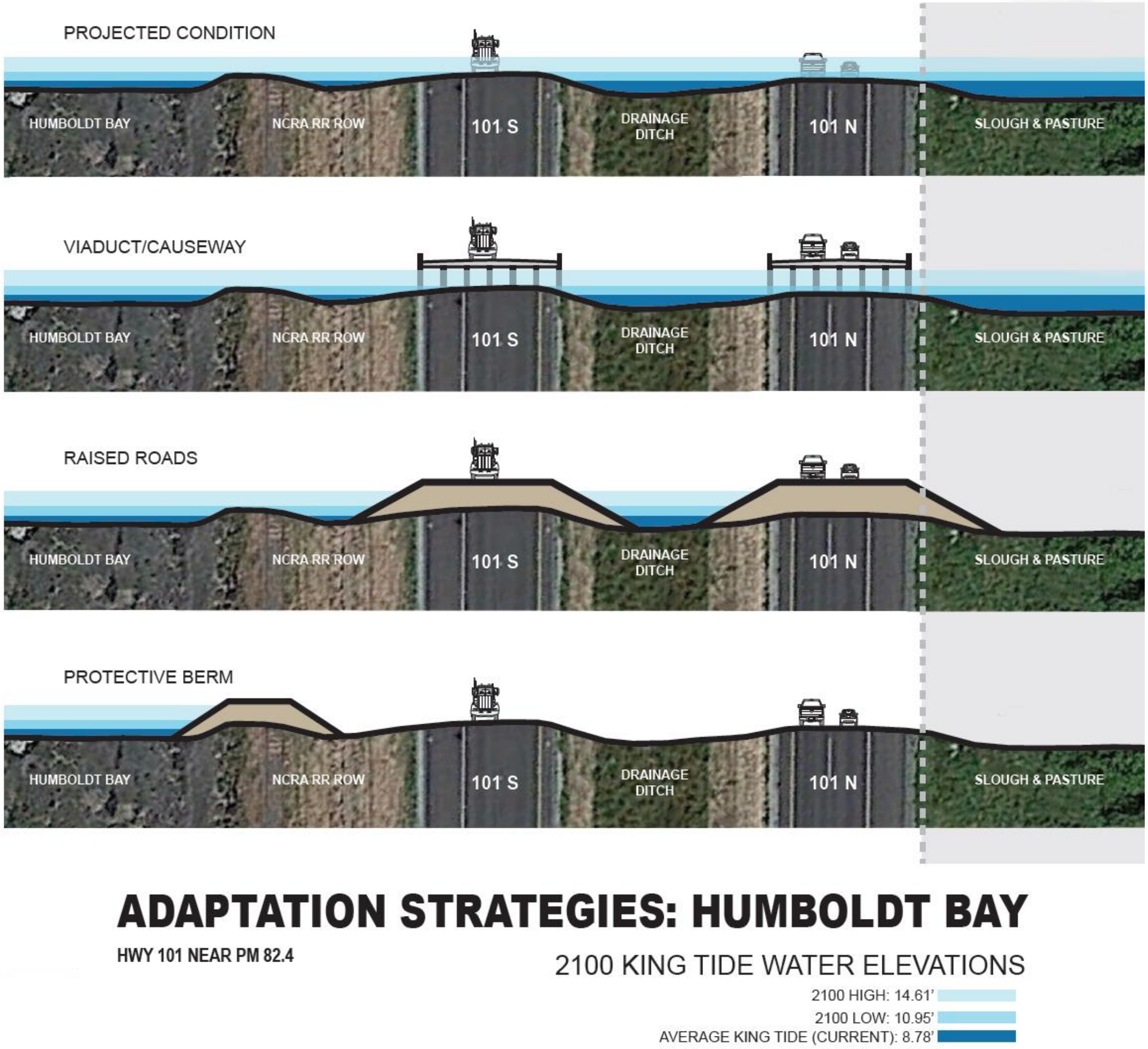

Figure 13: Adaptation Options for Humboldt Bay

Table 4 is a summary for Option 3, which is the temporary re-routing of traffic using Intelligent Transportation Systems (ITS):

Table 4: Humboldt Bay Example Scoring Sheet for Adaptation Option 3: Temporary Re-routing of Traffic Using ITS

Assessment Criteria	Value	Comments
Assumed Design Service Life	20 years	Typical useful life of ITS infrastructure is 20 years.
Assumed Total Capital Investment	$ 1,080,000 (same for 2050 and 2100)	The capital investment includes the ITS infrastructure. Also added to this option is the estimated annual cost of added maintenance and staff time for assisting with alternate routes ($50,000/ year for 20 years).
Usable Life	0: Minimal or temporary	The usable life is less than the 2050 or 2100 time frames and will allow flooding at King tides under existing conditions.
Level of Performance	1: Decreased	This option provides reduced performance relative to the existing condition.
Flexibility	3: Likely	This option allows flexibility to further evaluate climate impacts and allows for any option to be implemented in the future.
Environmental Considerations	-1: Very little net impact	Some flooding would occur under both the 2050 and 2100 scenarios
Social Considerations	-2: Some net impact (2050) -3: significant net impact (2100)	Alternate routes would be needed, creating delays for the traveling public. Delays would increase as time goes on with almost no access by 2100.

Table 5 ranks and summarizes the options scores and costs for the 2050 and 2100 climate scenario:

Table 5: Summary of Humboldt County Prototype Location Adaptation Options

Rank	Adaptation Option	Project Description	2050		2100	
			Score	Order of Magnitude Cost Estimate	Score	Order of Magnitude Cost Estimate
1	Provide protection at existing elevations/ locations	Strengthen/ add protection to existing protective structures (RR berm, dikes, and fill areas) for 10 miles, including increasing height to 1 ft above 2050/2100 water level at a King tide	189	$121,310,000	189	$121,460,000
2	Elevate the infrastructure above the impact zone	Increase the height of the roadway by building up the fill prism 1 ft above 2050/2100 water level at a King tide for 6 miles	152	$60,570,000	148	$117,630,000
3	Elevate the infrastructure above the impact zone	Construct a causeway, 6 miles, at a height of 5 ft above 2050 water level at a King tide	137	$173,680,000	137	$368,040,000
4	Relocate infrastructure (horizontally)	Assumed 8 mile re-route to the east of the existing Hwy 101	126	$350,000,000	126	$350,000,000
5	Increase the infrastructure's maintenance and inspection interval and continue to monitor/ evaluate	Equivalent to the No project alternative. Only temporary measures enacted and repairs made on an as needed basis.	30	$950,000	30	$950,000
6	Temporarily restrict use of infrastructure	Install ITS infrastructure to recommend use of alternate route and Increase signage and warning information	15	$1,080,000	15	$1,080,000

Lake County

Seven adaptation options were proposed for consideration for Highway 20/County Road 407, of which four were determined to be feasible. Option 1, Elevate the infrastructure above the impact zone, is shown in Table 6:

Table 6: Highway 20/County Road 407 Example Scoring Sheet for Adaptation Option 1: Elevate the Infrastructure Above the Impact Zone

Assessment Criteria	Value	Comments
Assumed Design Service Life	100 years	High end of the design life of an earthen structure. Assumed structure is properly maintained to protect integrity, and regular roadway overlays are implemented.
Assumed Total Capital Investment	$ 49,810,000	Assumed road is raised to above flood hazard elevation. Due to limited data on coastal flooding elevations, one cost was developed for 2050 and 2100
Usable Life	3: Surpasses	The usable life is beyond the 2100 scenario, thus, the option surpasses the climate horizon in its useful life
Level of Performance	3: Enhanced	This option provides enhanced performance relative to the existing condition.
Flexibility	1: Unlikely	With the costs and effort involved in constructing the new roadway on the raised fill prism, it would be difficult to add additional height in the future.
Environmental Considerations	-2: Some net impact	It is assumed that some wetlands would be impacted with a bigger fill footprint needed for an elevated road, and it would be more that raising the height of protective structures.
Social Considerations	3: Some net improvement	The use of the highway would be maintained, which provides a social benefit, however this option does not necessarily protect other social assets, such as telephone, gas, and water lines.

Table 7 ranks and summarizes the options and the score for the 2050 climate scenario:

Table 7: Summary of Lake County Prototype Location Adaptation Options

Rank	Adaptation Option	Project Description	Score 2050	Order of Magnitude Cost Estimate
1	Elevate the infrastructure above the impact zone	Increase height of roadway 2 ft above 100 yr flood hazard zone elevation. Project would incorporate new culverts and drainage features	163	$49,810,000
2	Relocate infrastructure (horizontally)	Assumed 4 mile re-route to the east of the existing Hwy 20 -Does not address CR 407	141	$140,000,000
3	Increase the infrastructure's maintenance and inspection interval and continue to monitor/evaluate	Equivalent to the No project alternative. Only temporary measures enacted and repairs made on an as needed basis.	30	$950,000
4	Temporarily restrict use of infrastructure	Install ITS infrastructure to recommend use of alternate route and Increase signage and warning information	15	$1,080,000

Mendocino County

Seven adaptation options were proposed for consideration, of which five were considered feasible and therefore appropriate for further study. Option 3, as shown in Table 8, proposes re-routing of Highway 1 along Windy Hollow Road. This would require construction of a new bridge. Option 3 is ranked number 2 , as Shown in Table 9.

Table 8: Garcia River Example Scoring Sheet for Adaptation Option 3: Re-route Highway 1 Along Windy Hollow Road

Assessment Criteria	Value	Comments
Assumed Design Service Life	100 years	High end of the design life of an earthen structure. Assumed structure is properly maintained to protect integrity
Assumed Total Capital Investment	$ 35,570,000	Road is permanently re-aligned, which is assumed to address both the 2050 and 2100 scenarios. Only one cost was developed
Usable Life	2: Acceptable	The usable life is beyond the 2100 scenario
Level of Performance	3: Enhanced	This option provides enhanced performance in comparison with the existing condition
Flexibility	3: Likely or Unnecessary	The new alignment would be out of the hazard zone, and thus, would not need to be flexible.
Environmental Considerations	-2: Some net impact	It is assumed that some wetlands may be impacted where Windy Hollow Road would be widened
Social Considerations	3: Significant net improvement	The use of the highway would be maintained, resulting in significant connectivity improvement. In addition, the new bridge would connect the Manchester Point Arena tribal lands.

Table 9 ranks and summarizes the options and the score for the 2050 climate scenario:

Table 9: Summary of Mendocino County Prototype Location Adaptation Options

Rank	Adaptation Option	Project Description	Score 2050	Order of Magnitude Cost Estimate
1	Elevate the infrastructure above the impact zone	Construct a causeway, across the Garcia River Flood plain and Hathaway Creek at a height of 5 ft above 100 yr coastal hazard elevation including 24 inches of SLR A2 Scenario @2050).	178	$15,520,000
2	Relocate infrastructure (horizontally)	Re-route Highway 1 along Windy Hollow Rd	167	$35,570,000
3	Elevate the infrastructure above the impact zone	Increase height of roadway 2 ft above 100 yr coastal hazard elevation including 24 inches of SLR (A2 Scenario @2050). Project would incorporate new culverts and raising/ replacing Hathaway Creek Bridge	152	$14,420,000
4	Temporarily restrict use of infrastructure	Temporarily re-route Highway 1 long Windy Hollow Rd during periods of flooding	85	$25,410,000
5	Increase the infrastructure's maintenance and inspection interval and continue to monitor/evaluate	Temporary close/ reroute during flooding (Assume closure 6 times per year in 2050 @ 12 hours average and 12 per year in 2100 @ 18 hours average)	-22	$219,600,000

4.4 Prioritization of Actions

The process of completing this study resulted in a number of valuable findings that can help direct future climate adaptation work. These findings ranged from planning for changes in maintenance and design practices to more detailed analysis of vulnerable assets. Three primary actions identified to build on the results of this study are discussed below.

4.4.1 Changes to Caltrans Planning and Design Policies

Incorporation of climate change considerations into the various levels of planning, design and operations and maintenance is an important action for Caltrans and other agencies to pursue. The results of this study indicate there is a need for Caltrans to review policies and practices to consider the longer term and multi-stakeholder issues associated with adaptations to climate change. The effects of climate change are not distributed uniformly across Caltrans jurisdiction. Climate change events can be episodic or chronic and so may affect assets either sporadically or persistently over time. The anticipated magnitude and distribution of the effects across Caltrans assets may exceed the availability of resources to completely defend against all climate change effects. It will be necessary for Caltrans to identify acceptable levels of services and prioritize adaptations through-out the State based on available resources. It is important that Caltrans climate change adaptation policies and practices are adaptable to adjust to lessons learned and insights from current and future studies.

One insight gained through this study is that the historical design standards such as the 100 year precipitation event may not be the most appropriate given the nature of climate change. Caltrans should consider working with the Federal Highways Administration, FEMA, and other agencies to update design standards to be more reflective of potential climate change and provide more adaptive capacity within new structures built. Designing to existing standards for the 100-year flood plain areas and depths, runoff volumes, and sea levels including wave run up, may not provide the functionality needed in the future to accommodate impacts from climate change. Close coordination with FEMA and other federal agencies providing updated planning data for flooding, runoff, and sea level rise will be needed. Caltrans can begin planning for changes in design standards that can improve the adaptive capacity of assets to handle changes related to climate change.

Another finding of this study was that the local maintenance staff are at the forefront of addressing the effects from extreme weather events today. While the use of climate change models and mapping are useful to vulnerability determinations, often the most vulnerable sites are already experiencing issues. These issues will tend to be exacerbated with the effects of climate change. Tracking this in a more accurate way would help provide data for climate change planning. It is recommended that Caltrans update the maintenance and repair data collection and tracking systems to include more site and event specific data such as precipitation conditions prior to maintenance events, location and type of maintenance activity, more detail on the type and mode of asset failure, and specific event dates will help Caltrans understand priority vulnerable assets better. These data should be collected uniformly throughout the state and contained in accessible data systems so planners and engineers can readily make use of the information.

Once policies and guidance have been established, training and development should take place to ensure all staff are aware of the needs and expectations regarding climate change and adaptation planning.

4.4.2 Coordination with Public Agencies and Private Landowners

Through this study, a better understanding of the dependencies between Caltrans assets and nearby public and private assets was gained. As Caltrans moves forward on climate change adaptation planning, it will be important to collaborate with other local and state agencies as well as private land owners. In some areas, Caltrans assets act to protect public and private lands and infrastructure, in other areas, Caltrans assets are protected by systems owned by others. Caltrans should get engaged in Local Coastal Plan updates that are incorporating projected climate change. The state highway system cannot adapt to climate change without the input and collaboration of others in nearby affected areas.

It will be important to consider multiple benefits to other vulnerable infrastructure when planning for adaptation. There may also be opportunities for cost sharing on adaptation measures when collaborative solutions are developed.

4.4.3 Site Specific Risk Analyses

As discussed above, the effects of climate change are not uniformly distributed across Caltrans assets and the effects are often sporadic. The effects can be magnified through multiple forces converging simultaneously. It would not be uncommon to have the precipitation and runoff effects of a severe storm combined with a storm surge driven by wind and a high tide during a future higher base sea level elevation. In fact, there are many degrees of high tides that occur throughout the year. There are other compounding effects that could be considered, such as seismic events.

It is not logical to simply combine a series of possible events into a “worst-case scenario” and design for that because, although the effects may be very dramatic, the likelihood may be very low. Therefore a statistically based approach can be used to simulate the combined likelihood and resulting effects. Through techniques such as a computer-based Monte Carlo Simulation, many thousands of iterations can be run and the results analyzed to evaluate the potential for combined effects. This can also be linked to a damage estimate model and an adaptation cost model to help select economical adaptation strategies.

This strategy represents a significant analysis and planning effort and it would be appropriate for areas where the potential for damage and disruption from climate change were significant as is the cost of defending against it. This technique should be developed at one of the prototype locations to demonstrate its effectiveness and to advance the planning for the location. This technique could be particularly useful for the Eureka Arcata corridor where the asset is large, the effects are significant, and there are many stakeholders. The results of the analysis could then be used to start to understand similar effects at other locations throughout the state highway system.

5. Lessons Learned

5.1 What Challenges, If Any, Did You Encounter, and How Did You Overcome Those Challenges?

Data collection and evaluation presented significant challenges to the project: large volumes of data needed to be sorted and combined in order to rank assets for criticality and potential for impact. The importance of the critical analysis of the data based on technical expertise and judgement is essential for making wise use of this data. It becomes necessary to segment large areas into fairly broad pieces that may contain multiple assets and so more focused studies on critical areas are required to adequately analyze vulnerability and adaptation options at the site-specific scale. Also, it was necessary to evaluate costs at a high level when considering multiple options. Once again, more detailed study could be undertaken to refine options and costs.

5.1.1 Obtaining and Applying the Information Used in This Project?

- There was so much data available. Making decisions to find and focus on relevant data was challenging. Deciding on the most useful format and most useful attributes was also challenging. This was addressed by building GIS models to categorize and automate data processing. Reflecting on the likely impacts to roads was key to developing filters for the data. Consulting with technical experts such as Caltrans staff via the TAG and Stakeholder Group was very helpful to hone in on data use and interpretation.
- While Caltrans itself collects data throughout its region, and provided a wealth of information, there are disparities elsewhere in resources and data collection. For example, Humboldt Bay is relatively well-studied compared to Pt. Arena, Crescent City, and sites in Lake County. Humboldt Bay hosts a large state university and many government natural resource offices. State and federally sourced data provided a common base for much of the work. Equivalent data sets, such as detailed sea level rise or flood studies, that would inform site-specific adaptation concepts, however, were difficult to obtain. These disparities resulted in less in-depth explorations of sites at different stages of the project.

5.1.2 Assessing Asset Vulnerability and Risk?

- It was difficult to assess the sensitivity of multiple assets to the frequency, duration and magnitude of climate change factors. While consulting with technical experts such as Caltrans staff via the TAG and Stakeholder Group was critical to making progress, detailed site-specific studies such as stochastic models that incorporate hydrologic and hydraulic data, topography and infrastructure components would be needed to better understand impacts of climate change factors. These were simply beyond the scope of this study and would generally require much more detailed site information.
- The criticality assessment is challenging because it is essentially a value judgment: what is critical for one person may not be critical for someone else. It is difficult to quantify this context and relativity.
- In attempting to better focus on criticality to address the challenge noted above, many potential measures were studied and weighed, building in redundancies. It created a false sense of detail and in overemphasizing some criteria, potentially had the effect of skewing weightings.

- It was important to be constantly checking the sensitivity of the information and findings (quality assurance and quality control), and questioning what drove particular scores.
- This highly involved process led to a ranked list of vulnerable assets. The process often validated what was already understood by the managers of the assets. There were few surprises regarding locations of vulnerability. This also highlights the observation that, in light of the limitations of site specific data, it may be more productive in regions where vulnerable assets are well understood to focus funding on more specific site/asset assessments.
- There is considerable variability between climate models. No one model is “right”, and it is impossible to precisely forecast the magnitude and timing of severe episodic events. Selecting climate models in light of this was challenging. Ultimately, climate models that were more conservative, for example the “wet” scenario for precipitation, were used to guide assessments.

5.1.3 Identifying, Assessing, and Selecting Adaptation Strategies?

- As this is a relatively new process, it was challenging to find detailed processes for this kind of project selection and analysis to use as a basis for adaptation selection. Most descriptions of adaptation processes were general. This was addressed by using the general formats available, analysing the effects of climate change factors on different aspects of the road system, and considering cause-and-effect for a range of adaptation options. This methodical breaking down of steps was captured in the spreadsheet selection and analysis tool. This was performed by looking at primary and secondary climate change effects, and generating a list of potential adaptation options in response to these effects.
- To create an automated system, climate change effects were simplified. This created some generalities that may not apply to all situations. For example, flooding from sea level rise and from increased runoff/precipitation may require different adaptation options. Flooding from increased runoff/precipitation may also arise in different ways depending on the specific siting and design of the infrastructure in question. For example, a blocked culvert may cause flooding as upstream flows accumulate behind the culvert. In such a case, a larger culvert may be the appropriate design solution. However, if flooding is the result of a downstream blockage or backwatering, a larger culvert does not address the issue; flood walls or raising of the structure above the backwater elevation may be needed. This was addressed by adding more options with more detail to the spreadsheet tool. This created, at one point, an overwhelming number of options. The options were then organized around broad classes to simplify the selection process.
- Cost estimating at this planning level is very conceptual. For comparisons between a projects that have order of magnitude differences (i.e. $5 million vs $80 million), the distinctions are reason-able; for evaluating two projects of about the same price (ie within 10-30% of each other), it is much more difficult. One way we addressed this is through the use of selection criteria to help with identifying priorities as well as costs. We also attempted to build more detail into the project concepts to achieve clearer project cost characterizations. Variables that could not be identified at this scale included detailed site information that would be required in a preliminary engineering study but was out of scope and budget for this project. For example, depth of a foundation, such as a causeway’s piles, to bedrock is a level of detail that would not be known at this level of study but could have a profound impact on cost.

- The public meetings provided a venue for information sharing about climate change impacts and soliciting information from the public regarding adaptation option priorities. Communicating highly technical information within a limited timeframe resulted in information-dense presentations. The public process was more of an educational tool that also provided preferential data to compare with stakeholder and TAG feedback.

5.2 Recommendations for Future Applications at Your Agency and Other Agencies. How Might Other Agencies or Areas Use Your Methods or Findings?

The vulnerability assessment and adaptation assessment tools were developed to automate selection processes and can be tailored to different kinds of infrastructure. Criteria and weightings could be adjusted according to the priorities of the agency and its stakeholders. The tools create a method for sifting through large volumes of data to identify potential areas of vulnerability across a large region, and create an opportunity for evaluating options based on criteria also established by the user group. Other regions could use these tools by inputting climate change data scaled to their region.

These findings provide validation of the impressions of maintenance staff and managers whose professional judgments have already identified vulnerable assets. The findings and concept level studies can also support engineering feasibility studies and provide preliminary assessments for environmental documents.

5.3 Recommendations for Changes or Additions to FHWA Vulnerability Assessment Framework, Including Additions to the Section on Analysis of Adaptation Options

An adaptation selection process that relies more on team expertise will likely identify viable adaptation options as quickly and efficiently as a tool that requires a user to scroll through primary and secondary climate effects. Retaining the tool for the evaluation of options identified, however, would remain a helpful and efficient element.

This project enabled a large landscape-scale analysis of asset vulnerabilities. As noted above, managers may already have an inherent understanding of their most vulnerable assets, and in those situations, planning may be more efficiently advanced by focusing on more site specific or detailed assessments.

The larger process may not always be needed to identify vulnerabilities at the local level; these tools may be more helpful for demonstrating vulnerabilities to state or federal agencies charged with establishing policies that affect local or regional-scale entities.

Guidance to tailor design storms, such as the 100-year storm, to account for climate change would be a helpful future project or tool that could be developed through FHWA funding for use by transportation agencies. A similar guidance document for sea level rise was published by the California Coastal Commission and was used in this study.

6. Conclusions and Next Steps

6.1 Project Successes and Accomplishments

This project advanced awareness of the climate change risks posed to communities and infrastructure, and provoked enlightening discussions about planning, criticality, and the future of the state road system. Tools were developed that provide partial automation of data processing and can expedite the assessment of climate risks to different kinds of infrastructure. Findings from the project are informing existing projects and demonstrating opportunities to leverage resources.

6.1.1 Key Accomplishments

- Development of tools that, once tailored with local data, automate data processing and rapidly assess asset criticality, potential for impact, vulnerability and adaptation options;
- Advancement of a process that improves adaptation planning;
- Raised awareness of climate change impacts throughout District 1, including with the general public;
- Raised awareness of the need for more focused baseline study of less populated regions.
- Supported enhanced regional dialogues about climate change
- Produced climate change estimates and adaptation concepts that are informing current, ongoing project planning.
- Some adaptation options present multiple or leveraged benefits:
    - In Lake County, adaptation options can support ongoing wetland restoration efforts at Rodman Slough by eliminating flood hazards;
    - In Humboldt Bay, there is the possibility that adaptation options can minimize flood risks to existing diked tidelands; alternatively, adaptation options can restore tidal processes and wetland habitats;
    - In Mendocino County, the more popular adaptation option (road relocation), supports local goals and can leverage local funding.

6.1.2 Summary of Project Metrics

The project inventoried and analyzed over 16,000 Caltrans assets against a 2050 and 2100 climate change threshold and 2 climate models. Ninety-three road segments representing almost 980 miles over 23 Caltrans roadways were ranked for vulnerability using weighting and scoring criteria scaled with input of TAG and Stakeholders. Adaptation options for four pilot project sites were also scored using weighted criteria informed by input of TAG, Stakeholders and members of the public. Twenty-four members of the TAG, 59 stakeholders, and 119 members of the public were reached during the project process.

Proposed adaptation projects would prevent strandings and ensure high level of service in Pt Arena/Stornetta area; maintain a lifeline to Crescent City; reduce traffic diversions and disruptions of service in Humboldt Bay; and minimize re-routing and delays in Lake County. Comments received from the TAG on the Draft Final D1CCPS Report are included in **Appendix 12**.

There were several digital deliverables associated with this project including GIS data and the final adaptation tool. Appendix 13 to this report includes a summary of the digital data. The digital files are provided under separate cover.

6.2 Planned and Anticipated Next Steps

Findings from this study are supporting current studies on Highway 101 at Last Chance Grade in Del Norte County and informing dialogues on design on a planned interchange on Highway 101 in Humboldt Bay. The adaptation options explored in Mendocino County are providing information to assist the local transportation planning agency, Mendocino Council of Governments, in their assessment of routing options over the Garcia River. Findings for the Lake County road segment can be used by agencies working on Middle Creek/Rodman Slough restoration to inform their planning.

Climate change vulnerability findings at the regional scale will be a reference tool for local transportation planning agencies in District 1. The Humboldt County Association of Governments is planning on presenting findings to its board, and is promoting use of the tools locally.

7. Appendices

Appendices are available on Caltrans District 1 website at:

http://www.dot.ca.gov/dist1/d1transplan/system_planning/ccps/

Appendix 1	**Caltrans TCR Segment Criticality**
Appendix 2	**Climate Data Projections for Caltrans District 1 Climate Change Pilot Study**
Appendix 3	**Caltrans TCR Segment Potential for Impact**
Appendix 4	**Caltrans TCR Segment Vulnerability**
Appendix 5	**Caltrans Asset Adaptation Assessment Methodology**
Appendix 6	**Caltrans Asset Adaptation Assessment** **Del Norte County Prototype Location**
Appendix 7	**Caltrans Asset Adaptation Assessment** **Humboldt County Prototype Location**
Appendix 8	**Caltrans Asset Adaptation Assessment** **Lake County Prototype Location**
Appendix 9	**Caltrans Asset Adaptation Assessment** **Mendocino County Prototype Location**
Appendix 10	**Stakeholder and Public Meeting Summary**
Appendix 11	**Scope of Work**
Appendix 12	**Draft Final Report Comments**
Appendix 13	**Guide to Digital Resources**