HAWAI‘I DEPARTMENT OF TRANSPORTATION
HIGHWAYS DIVISION

HAWAII HIGHWAYS
Climate Adaptation Action Plan
EXPOSURE ASSESSMENTS

April, 2021

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

Acronym	Description
AASHTO	American Association of State Highway and Transportation Officials
BrM	Bridge Condition Dataset
CMIP5	Coupled Model Intercomparison Project
DEM	Digital Elevation Model
DSM	Digital Surface Model
EOC	Emergency Operations Center
FHWA	Federal Highway Administration
FOS	Factors of Safety
GCM	Global Climate Model
HDOT	State of Hawai'i Department of Transportation
HPMS	Highway Performance Monitoring System Roads for Hawai'i
HRCM	Hawai'i Regional Climate Model Simulations
HVO	Hawaiian Volcano Observatory
IPCC	Intergovernmental Panel on Climate Change
LiDAR	Light Detection and Ranging
LTD	Local Tidal Datum
NEOWAVE	Non-hydrostatic Evolution of Ocean Wave
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PDO	Pacific Decadal Oscillation
RCP4.5	The representative concentration pathway that reaches 4.5 watts per meter squared of warming by end-of-century
RCP8.5	The representative concentration pathway that reaches 8.5 watts per meter squared of warming by end-of-century
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
USGS	United States Geological Survey
WCRP	World Climate Research Programme
WRF	Weather Research and Forecasting

EXECUTIVE SUMMARY

The Hawai‘i Highways Climate Adaptation Action Plan (the Action Plan) includes locations along 917.1 miles of State roads, including 397 bridges, 73 culverts, and 6 tunnels, that are exposed to a range of climate-related hazards and lava flow hazard. These locations are identified through exposure assessments, which help determine the highway assets that are in areas where hazard events may occur now—and for some hazards, such as those related to sea level rise scenarios, in the future—due to changing environmental conditions. These assessments can be used to prioritize detailed vulnerability, risk, and resilience studies, leading to an increased understanding of the probable socioeconomic consequences of these hazard events and informed climate adaptation decisions.

Chapter 1 of this report describes the assets, namely road sections, bridges, culverts, and tunnels, considered in the exposure assessments. Chapter 2 describes the available precipitation and temperature data projections available for Hawai‘i. Chapter 3 through Chapter 8 document the exposure assessments conducted for the following hazards: rockfalls and landslides, chronic coastal flooding (i.e., marine inundation, groundwater inundation, annual high wave flooding, and coastal erosion), storm surges, tsunamis, wildfires, and lava flows. Brief descriptions of how the exposed assets were identified are provided in Table ES-1. Given the limited precipitation and inland flood data available, determining the exposure of assets to inland flooding was deferred to future work. Additional exposure assessments (e.g., extreme temperature) also should be undertaken in the future.

Table ES-1. Determination of State roads, bridges, culverts, and tunnels exposed to climate-related hazards and lava flow hazard

Hazards	Identification of exposed assets
Rockfall and landslide	Segments associated with sites prioritized in the State of Hawai‘i Department of Transportation’s Rockfall Protection Program and sites determined to have high and very high susceptibility according to the United States Geological Survey (refer to Chapter 3)
Passive flooding	Segments exposed to marine flooding and groundwater inundation considering three sea level rise scenarios (refer to Chapter 4)
Annual high wave flooding	Segments exposed to annual high wave flooding considering three sea level rise scenarios (refer to Chapter 4)
Coastal erosion	Segments exposed to coastal erosion considering three sea level rise scenarios (refer to Chapter 4)
Storm surge	Segments exposed to storm surge due to Category 1 through 4 hurricanes (refer to Chapter 5)
Tsunami	Segments exposed to historical (1946, 1952, 1957, 1960, and 1964) and hypothetical tsunamis (two great Aleutian earthquakes with moment magnitudes of 9.3 and 9.6) (refer to Chapter 6)
Wildfire	Segments associated with 1-km2 areas where more than one wildfire ignition occurred between 2000 and 2012 (refer to Chapter 7)
Lava flow	Segments associated with lava flow hazard Zones 1 through 3 on the Island of Hawai‘i and Zone 1 in the Maui District (refer to Chapter 8)

Each of the exposure assessment chapters provides (1) information on previous works and existing data, (2) the methodology used for determining the exposure of assets to the hazard of interest, (3) the results of the application of the methodology, along with tables and figures to communicate the degree to which assets may be affected, (4) recommendations for Highways, and (5) recommended improvements to existing data and models to support the assessment of risk and resilience related to the State road network. Each of the assessments uses the latest data and methods available, generated or developed by local, national, and international actors (e.g., the State of Hawai‘i Department of Transportation, the University of Hawai‘i at Mānoa, the National Oceanic and Atmospheric Administration, the United States Geological Survey, and the Intergovernmental Panel on Climate Change).

The results of the exposure assessments indicate that approximately 564 miles of roads (58% of the assessed network) are exposed to climate-related hazards and lava flow hazard. This asset exposure includes 303 bridges (76% of the assessed bridges), 48 culverts (66% of the assessed culverts) and 6 tunnels (100% of the assessed tunnels). While these results may be accessed using the companion web map viewer, a summary of asset exposure by hazard is presented in Table ES-2.

Table ES-2. Distribution of State roads, bridges, culverts, and tunnels exposed to climate-related hazards and lava flow hazard

Hazard	Roads		Bridges		Culverts		Tunnels	
	(miles)	%	(units)	%	(units)	%	(units)	%
Rockfall and landslide	167.58	17%	126	32%	11	15%	6	100%
Passive flooding	9.38	1%	92	23%	7	10%	0	0%
Annual high wave flooding	23.93	2%	50	13%	6	8%	0	0%
Coastal erosion	23.74	2%	22	6%	2	3%	0	0%
Storm surge	74.14	8%	120	30%	9	12%	0	0%
Tsunami	178.06	18%	135	34%	15	21%	0	0%
Wildfire	139.20	14%	97	24%	18	25%	0	0%
Lava flow	151.78	16%	18	5%	15	21%	0	0%
All hazards	563.65	58%	303	76%	48	66%	6	100%

The results of the exposure assessments are presented in the following chapters by the four Districts of the State of Hawai‘i Department of Transportation: (1) Kaua‘i District, covering the island of Kaua‘i, (2) O‘ahu District, covering the island of O‘ahu, (3) Maui District, covering the islands of Maui, Molokai, and Lanai, and (4) Hawai‘i District, covering the Big Island. Examples of hazard-specific exposed areas are shown in Table ES-3.

Areas of concern overlap across hazards in some instances (e.g., between annual high wave flooding and coastal erosion, and between storm surge and tsunami). This is due to the spatial correlation of the studied hazards. Figure ES-1 through Figure ES-4 show key sites where multiple hazards may occur, represented by the density of road segments that are exposed to climate-related hazards and lava flow hazard. Low density indicates segments exposed to a low number of hazards, and high density indicates segments exposed to a high number of hazards.

Table ES-3. Examples of exposed areas

Hazards	Examples of exposed areas
Rockfall and landslide	» Kaua‘i District: portions of Kūhiō Highway in Hanalei and near Wainiha; Waimea Canyon Road and Koke‘e Road. » O‘ahu District: portions of Farrington Highway near Mākua Beach and Nānākuli; along Likelike Highway and Pali Highway; along Kalaniana‘ole Highway in Waimānalo. » Maui District: Hāna Highway in East Maui; portions of Honoapi‘ilani Highway in West Maui. » Hawai‘i District: Māmalahoa Highway on Hāmākua Coast.
Passive flooding	» Kaua‘i District: portions of North, West, and East Kaua‘i, including Kūhiō Highway between Hanalei and Wainiha; Kaumuali‘i Highway in Kekaha/Waimea; Kūhiō Highway over Wailua River and through Kapa‘a. » O‘ahu District: portions of Farrington Highway on the Wai‘anae Coast; Kamehemaha Highway on the North Shore and Windward shore (Kahana to Kahuku), Sand Island and Ala Moana Boulevard; Kalaniana‘ole Highway in Hawai‘i Kai. » Maui District: North Kihei Road by Kealia Pond; portions of Kamehameha V Highway on the south coast of Moloka‘i.
Annual high wave flooding	» Kaua‘i District: portions of North, West, and East Kaua‘i, including Kūhiō Highway between Hanalei and Wainiha; Kaumuali‘i Highway in Kekaha/Waimea; Kūhiō Highway over Wailua River and through Kapa‘a. » O‘ahu District: portions of of Kamehemaha Highway on the North Shore and Windward shore (Kualoa to La‘ie); Ala Moana Boulevard; Kalaniana‘ole Highway in Hawai‘i Kai and Waimānalo. » Maui District: portions of Honoapi‘ilani Highway in West Maui (Lahaina to Olowalu); North Kihei Road by Kealia Pond.
Coastal erosion	» Kaua‘i District: portions of North, West, and East Kaua‘i, including Kūhiō Highway between Hanalei and Wainiha; Kaumuali‘i Highway in Kekaha; Kūhiō Highway by Wailua River and Kapa‘a. » O‘ahu District: portions of Farrington Highway on the Wai‘anae Coast; Kamehemaha Highway on the North Shore and Windward shore (Kualoa to La‘ie), Kalaniana‘ole Highway in Waimānalo. » Maui District: portions of Honoapi‘ilani Highway in West Maui (Lahaina to Olowalu); North Kihei Road by Kealia Pond.
Storm surge	» Kaua‘i District: portions of North, West, and East Kaua‘i, including Kūhiō Highway between Hanalei and Wainiha; Kaumuali‘i Highway in Kekaha/Waimea; Kūhiō Highway over Wailua River and through Kapa‘a. » O‘ahu District: portions of Farrington Highway on the Wai‘anae Coast, Ewa Beach, areas of Kamehemaha Highway on the North Shore and Windward shore (Kualoa to La‘ie); Sand Island , Nimitz Highway, and Ala Moana Boulevard; Kalaniana‘ole Highway through Hawai‘i Kai. » Maui District: portions of Honoapi‘ilani Highway in West Maui (Olowalu to Pāpalaua); North Kihei Road by Kealia Pond; roads surrounding Kahului Harbor; portions of Kamehameha V Highway on the south coast of Moloka‘i. » Hawai‘i District: roads along Hilo Bay and Kawaihae Harbor.
Tsunami	» Kaua‘i District: portions of North, West, and East Kaua‘i, including Kūhiō Highway between Hanalei and Hā‘ena; Kaumuali‘i Highway in Kekaha/Waimea; Kūhiō Highway over Wailua River and through Kapa‘a. » O‘ahu District: most coastal roads of O‘ahu, including Kamehameha Highway and Farrington Highway; Sand Island , Nimitz Highway, and Ala Moana Boulevard; Kalaniana‘ole Highway through Hawai‘i Kai and Waimānalo. » Maui District: roads in West and Central Maui, including Honoapi‘ilani Highway and Hana Highway to Spreckelsville/Paia; Kamehameha V Highway on the south coast of Moloka‘i. » Hawai‘i District: roads along Hilo Bay and Kawaihae Harbor.
Wildfire	» Kaua‘i District: portions of Kūhiō Highway including Līhu‘e and Kapa‘a areas. » O‘ahu District: Leeward O‘ahu, including Wai‘anae Coast, ‘Ewa, Pearl City, urban Honolulu, as well as Wahiawā and Hale‘iwa. » Maui District: roads in Kahului, Kīhei, and Lahaina areas. » Hawai‘i District: portions of Queen Ka‘ahumanu Highway on the Kona Coast.
Lava flow	» Hawai‘i District: portions of Māmalahoa Highway/Hawai‘i Belt Road through Hilo, Puna, and Volcano area to Kailua-Kona; Queen Ka‘ahumanu Highway and Māmalahoa Highway mauka of Waikoloa Village.

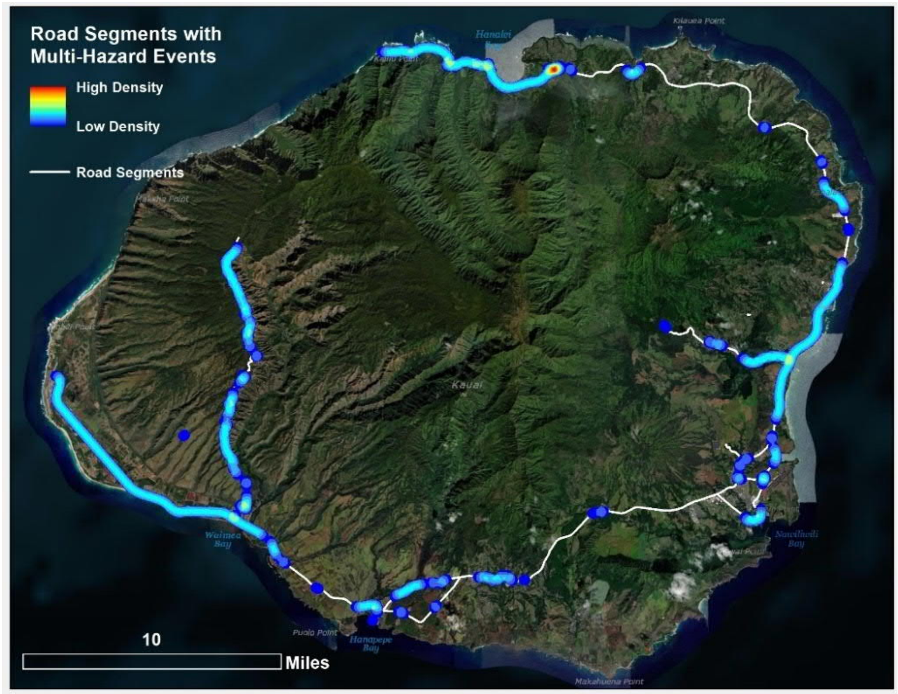

Figure ES-1. State road segments in the Kauaʻi District exposed to one or more hazards [1,2]

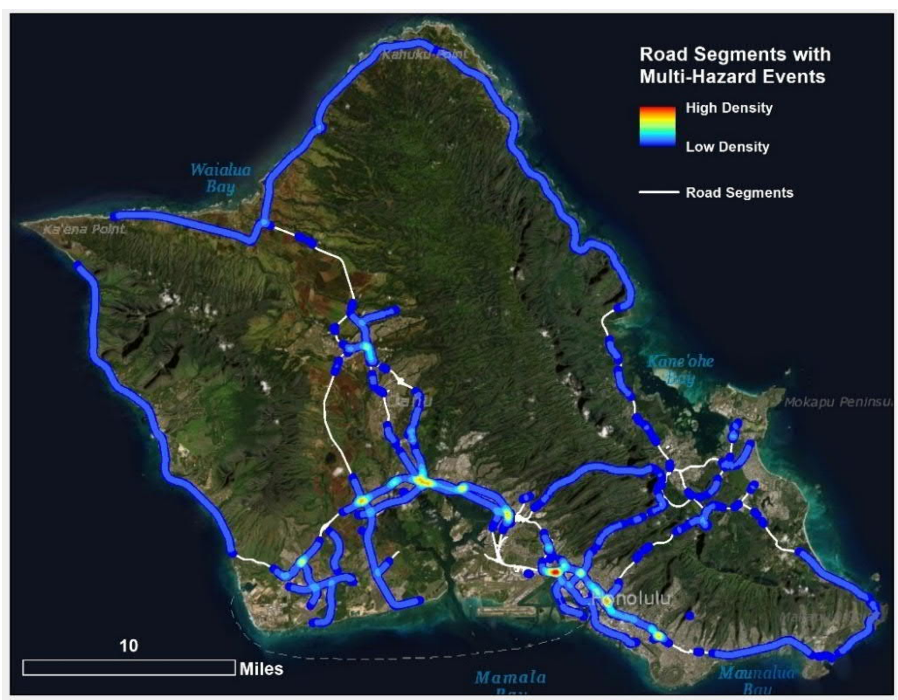

Figure ES-2. State road segments in the Oʻahu District exposed to one or more hazards [1,2]

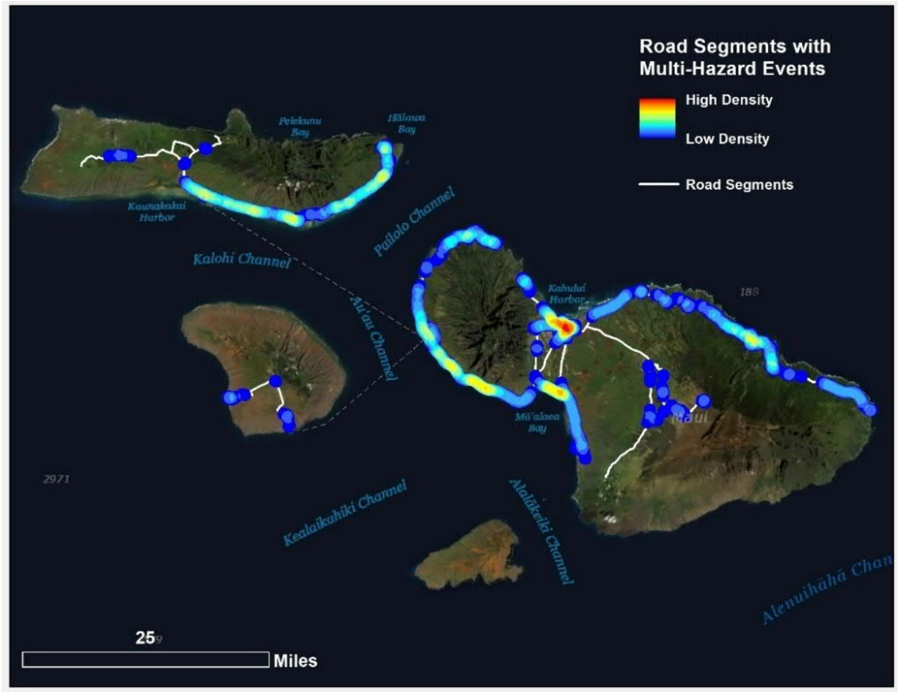

Figure ES-3. State road segments in the Maui District exposed to one or more hazards [1,2]

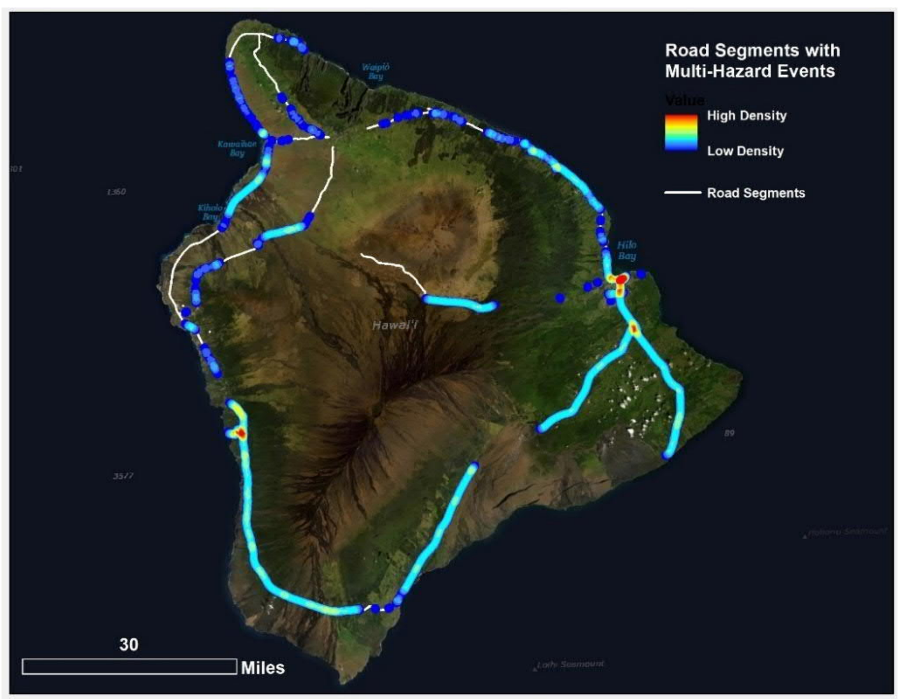

Figure ES-4. State road segments in the Hawai'i District exposed to one or more hazards [1,2]

This report contains 36 thematic recommendations mainly focused on programs, partnerships, and data. These recommendations are documented in Appendix A of the Action Plan, and are summarized in the following 12 general recommendations:

1. Improving asset inventory data and data synergy between follow-up efforts and those associated with existing data systems in the organization
2. Improving datasets used as additional inputs to this assessment, from elevation models (needing higher spatial resolution) to precipitation and temperature data (needing higher temporal resolution) and data associated with climate-related hazards and lava hazard (e.g., the need to increase spatial coverage of specific sea level rise hazards)
3. Conducting site visits to confirm the results of the exposure assessments, which were conducted using high-level analyses
4. Partnering with the University of Hawai‘i at Mānoa and other local and national organizations to generate the hazard event catalogs using stochastic modeling and probabilistic methods to account for uncertainties and combining these events with climate data projections to understand how such events may change over time
5. Informing the Rockfall Protection Program using the data generated in the rockfall and landslide exposure assessment
6. Supporting the implementation and expansion of hazard monitoring programs and early warning systems
7. Evaluating bridges exposed to coastal hazards, specifically tsunamis and storm surge, using available (or soon to be available) Federal guidance specifications, and improving this evaluation after improving the hazard data available to consider climate change
8. Improving the understanding of groundwater inundation as a threat to existing assets in low-laying areas
9. Evaluating the redundancy of the network to identify areas critical to the performance of the network
10. Engaging with State and local agencies planning and managing the retreat process of communities to inform capital planning and maintenance teams
11. Participating in the process of updating evacuation routes and emergency response planning tools
12. Improving the communication with Emergency Operations Centers to ensure resources are allocated for the prompt restoration of road services to support the delivery of emergency response services and the recovery of impacted communities

The data-related recommendations are important to advance this work from an exposure assessment to a risk and resilience assessment that considers climate change. This latter assessment would require the collection of additional information and methods to bring together hazard, asset vulnerability, and consequence data into a framework supporting the prioritization and investment of climate adaptation measures.

CHAPTER 1. ASSET INVENTORY FOR THE EXPOSURE ASSESSMENTS

1.1. BACKGROUND

The exposure assessment of the assets owned by the State of Hawai‘i Department of Transportation (HDOT) to probable hazard events, whether climate-related or non-climate-related, requires (1) the identification of all assets of interest, (2) spatial location, including elevation, and (3) their proper characterization. These elements are often referred to as the asset inventory. This assessment also demands (1) the identification of (natural) hazards that may impact the structural or functional performance of assets in the inventory, (2) the proper characterization of these hazards, including the definition of their spatial boundaries, and (3) the determination of the level of asset exposure to the considered hazard events (i.e., the assets that are within the hazards' spatial boundaries). This appendix describes the asset inventory and the elevation models used to determine the elevation of these assets when required by the exposure assessments. The modeling of hazards may have already integrated these elevation models (i.e., spatial boundaries consider elevation). For example, the modeling of chronic coastal flooding, storm surge and tsunami required the use of elevation models.

1.2. GEOREFERENCED ASSET DATA

State road network. The 2018 Highway Performance Monitoring System (HPMS) Roads for Hawai‘i [1], which represents 971.1 miles of existing HDOT assets, was used for this study. This dataset includes valuable location information such as route ID and mileage information for the beginning and ending of road segments, as well as important characteristics, including functional class (i.e., interstate, principal arterial, minor arterial) and type of surface. The HPMS dataset is segmented into 13,220 sections with an average length of 0.07 mile. These sections were further segmented into sections of 0.01-mile length to improve the location of areas exposed to hazard events. Table 1-1 provides a summary of the road network. Figure 1-1 through Figure 1-4 show these assets by District.

Table 1-1. Summary of State roads, bridges, culverts, and tunnels included in the asset inventory

District	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kaua‘i	103.3	44	7	0
O‘ahu	289.2	174	19	5
Maui	243.1	97	11	1
Hawai‘i	335.4	82	36	0
Total	971.1	397	73	6

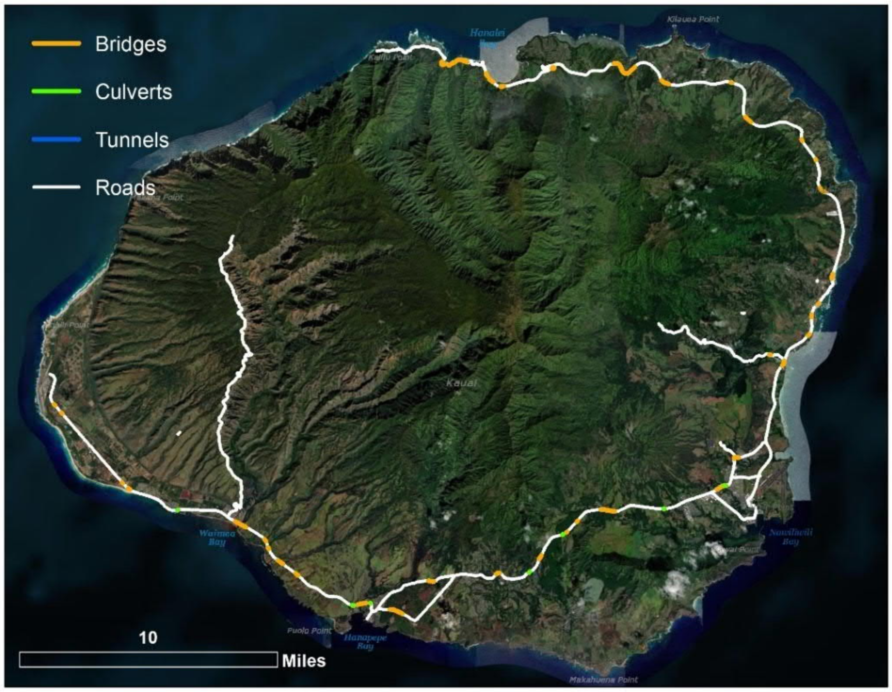

Figure 1-1. State roads, bridges, culverts, and tunnels in the Kaua‘i District[1,3,5,2]

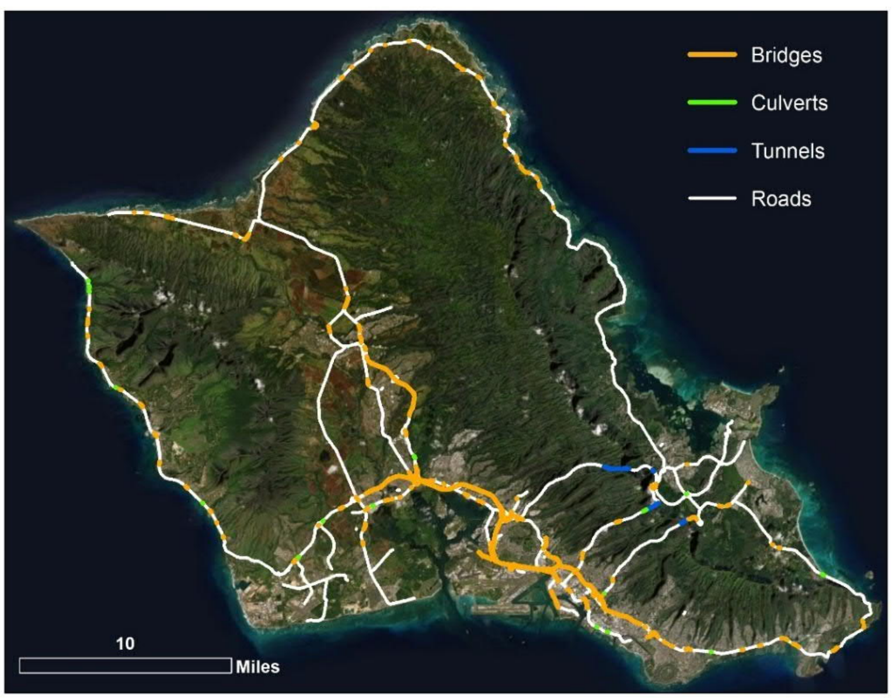

Figure 1-2. State roads, bridges, culverts, and tunnels in the O‘ahu District [1,3,5,2]

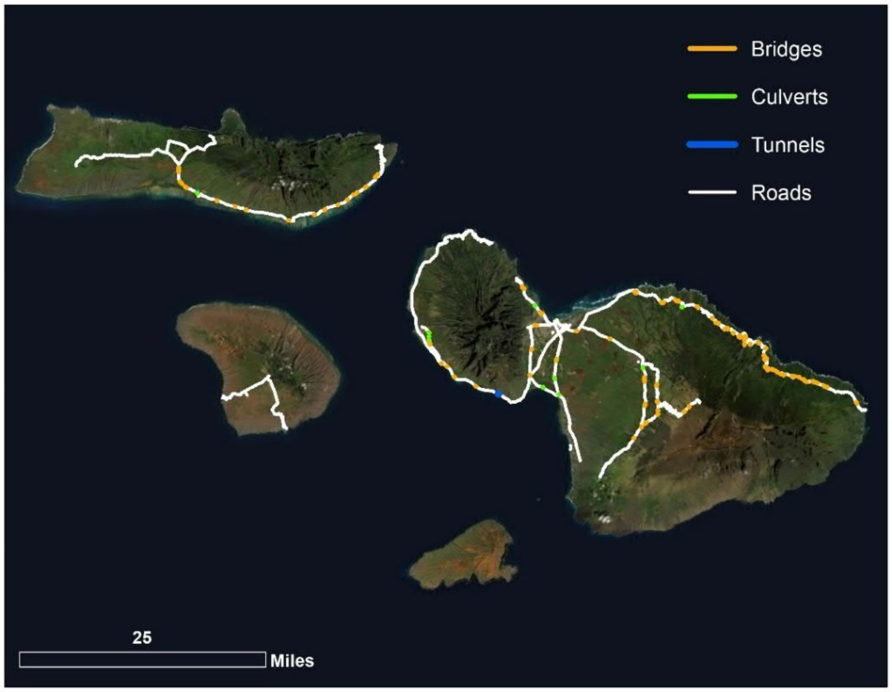

Figure 1-3. State roads, bridges, culverts, and tunnels in the Maui District [1,3,5,2]

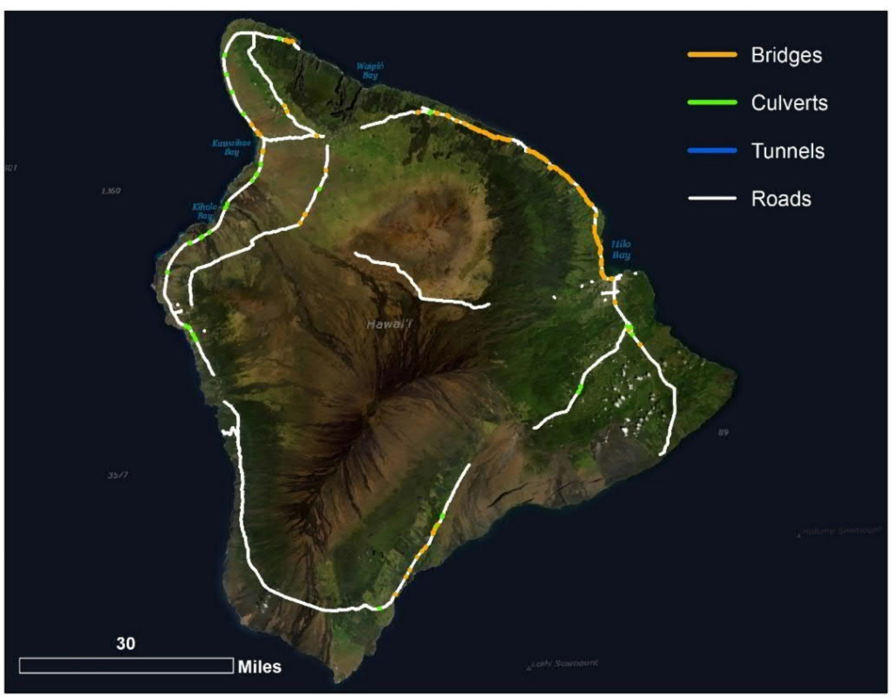

Figure 1-4. State roads, bridges, culverts, and tunnels in the Hawai'i District [1,3,5,2]

Bridges and culverts. The Bridge Condition Dataset (BrM) [3] from HDOT was collected to catalog bridges and culverts of at least 20 feet in span length. The dataset consists of 745 records (644 bridges and 101 culverts) under HDOT ownership. The BrM dataset includes operational specifications, conditions, dimensions, and functional descriptions, and is used to produce the National Bridge Inventory [4]. The dataset is defined geographically as point locations, which have varying degrees of accuracy when visually inspected against georeferenced datasets such as the State road network, aerial photos, and terrain data (i.e., points may be located anywhere along length of the road or adjacent to the bridge or culvert).

To define bridges and culverts as linear features rather than point features to capture their length along the road and improve the results of the exposure assessments, the geospatial locations of the point data were first corrected using available Degrees Minutes Seconds coordinate data. Data points located within 100 feet of the State road network were assigned to the nearest road section (a short distance of 100 feet was used to reduce false-positive assignments). The extents of bridge and culvert linear features were estimated using available length data. This process resulted in 470 linear features (397 bridges and 73 culverts) assigned to the State road network owned by HDOT. Table 1-1 provides a summary of the bridges and culverts. Figure 1-1 through Figure 1-4 show these assets by District.

Tunnels. The National Tunnel Inventory [5] was used for this study. The dataset consists of 11 inbound and outbound tunnel point locations. To define tunnels as linear features rather than point features, a process similar to that for bridges and culverts was followed. This process resulted in six linear features assigned to the State road network owned by HDOT. Table 1-1 provides a summary of the tunnels. Figure 1-1 through Figure 1-4 show these assets by District.

1.3. ELEVATION MODELS

The primary sources of elevation information available in coastal areas of Hawai‘i are a Digital Elevation Model (DEM) and a Digital Surface Model (DSM) of 1-meter resolution, which are derived from Light Detection and Ranging (LiDAR) data collected between 1997 and 2017 [6]. Approximately 17% of the State's total land mass is covered, representing approximately 60% of the State road network, much of which comprises belt road networks on most islands. Most of the network outside of the areas covered by the 1-meter elevation data is located in the mauka areas of the Districts of Kaua‘i, Hawai‘i, and Maui. Geospatial data collected in Hawai‘i are often referenced to as Local Tidal Datum (LTD). The vertical datum of this LiDAR data collection varies because Hawai‘i does not have a definitive geoid model. Metadata associated with the LiDAR collection indicates that data were collected in LTD for some islands, and data on other islands were collected without explicitly defining a vertical datum. The National Geodetic Survey will be releasing new horizontal and vertical datums for the National Spatial Reference System [7]. The anticipated release date is 2022. The State's asset inventory should be updated to the most recent horizontal and vertical datums statewide (i.e., all assets on the same datum).

For assets without 1-meter coverage, a second DEM prepared by the United States Geological Survey (USGS) is available [8]. This DEM has statewide coverage and a resolution of approximately 10 meters, and is referenced to LTD. Other elevation datasets were also identified (e.g., [9,10,11]); however, their utility to this study is limited (e.g., bathymetric applications, lower resolution, and sparse coverage) and their inclusion deemed unnecessary at this time. As part of the exposure assessment, DEMs can be used to characterize vertical measures of HDOT assets at ground level (e.g., roads and base of bridges), and the DSM can be used to compute elevated measures of assets (e.g., top of bridges).

1.4. RECOMMENDATIONS TO IMPROVE GEOREFERENCED ASSET DATA AND ELEVATION MODELS

» **Recommendation 1-1.** Future work should consider improving the asset inventory by integrating other assets such as (1) culverts with span length of less than 20 feet, which may be obtained from stormwater management systems (e.g., [12,13]), and (2) county assets in the inventory to assess the overall performance of the road network. The asset inventory may be further improved by including dual carriageways not represented in the HPMS dataset used in this study, and spatially capturing the correct location and length along the road of bridges, culverts, and tunnels.

» **Recommendation 1-2.** Future work should consider the use of the point cloud data accessible through HDOT's Roadview Explorer [14]. These data have the accuracy required to precisely locate the relative position and elevation of assets and asset components (e.g., bridge deck) and determine their geometries. This information can enhance HDOT's capabilities to determine the level of exposure of assets and their vulnerability, including those of specific asset components, to hazard loads.

» **Recommendation 1-3.** Future work should also be focused on determining a suitable data exchange method to automate the consumption of the results of the exposure assessments by other HDOT information systems, some of which may use these results in posterior analyses.

» **Recommendation 1-4.** Approximately 40% of the State road network is without 1-meter DEM coverage. This part of the network plays a critical role in the connectivity of coastal communities and in the redundancy of the entire road network. Therefore, expanding the coverage of the 1-meter resolution DEM would establish a continuity of statewide elevation data and would improve the elevation characterization of those HDOT assets as well as the assessment of hazards originating inland (e.g., [15,16]). The USGS 3D Elevation Program [17] was created to support the generation of high-quality elevation data for the United States, including Hawai‘i [18]. Future work should consider collaboration with USGS to identify priority areas in Hawai‘i that could benefit from better elevation data.

CHAPTER 2. **PRECIPITATION AND TEMPERATURE PROJECTIONS**

2.1. OVERVIEW OF CLIMATE PROJECTIONS

Climate projections are used to assess which assets may be exposed to future hazards under a changing climate. The World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP5) [19] provides climate projections from more than 30 global climate models (GCMs) that can be used to inform such assessments and other works focused on evaluating the impact of future climates (e.g., the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [20]). These GCMs can simulate how climate may evolve under future conditions, including changes in greenhouse gas concentrations that represent societal changes over the coming century (e.g., use of fossil fuels, population growth, technological advances).

2.2. CLIMATE PROJECTION DATA FOR HAWAIʻI

The spatial resolution of the climate projections generated by the GCMs (e.g., 1 degree latitude by 1 degree longitude) is too coarse for Hawaiʻi, and does not account for local conditions. The application of methods to downscale climate projections to finer grid resolution can be challenging in Hawaiʻi due to the following:

- The steep and varied terrain across the islands, which influences precipitation and wind patterns
- The long-term swings in precipitation due to interdecadal and interannual phenomena (e.g., the Pacific Decadal Oscillation (PDO), El Nino) [21]
- The intra-annual precipitation and wind bimodal patterns during the wet season (November–April) and the dry season (May–October)
- Small-scale phenomena such as trade wind regimes, Kona storms, land-sea breezes, localized convection, inversion layers, and tropical cyclones

As shown in Table 2-1, two methods have been applied to downscale WCRP CMIP5 data for Hawaiʻi using:

- Statistical downscaling, which develops statistical relationships between the GCM grid cell results and the observational data, and the application of these relationships to future GCM data
- Dynamical downscaling, which drives the high-resolution regional climate model with GCM data

2.3. METHODOLOGY

Statistically downscaled temperature and precipitation data [22,23] were used to inform the exposure assessments because of the range of time periods and scenarios available for evaluating future exposure. The data considered two emissions scenarios for mid-century and end-of-century conditions:

- A moderate warming scenario, where greenhouse gas emissions continue to increase until 2040 and then decline reaching a stabilization in concentrations by the end of the century (i.e., the representative concentration pathway that reaches 4.5 watts per meter squared of warming by end-of-century, or RCP4.5)
- A high warming scenario, where greenhouse gas emissions continue to increase through the century (i.e., the representative concentration pathway that reaches 8.5 watts per meter squared of warming by end-of-century, RCP8.5).

2.4. PRECIPITATION

Based on the available projections, the analysis of precipitation data was focused on understanding changes during the wet season to account for major storms and torrential rains. The future percent changes in precipitation of [22] (i.e., the mean of the GCM ensemble) were applied to the historical seasonal data averaged across years (1978-2007) [24] to obtain possible future precipitation values during the wet season. Figure 2-1 through Figure 2-12 illustrate part of the results. These data suggest a decrease in wet-season precipitation. The exception is along and above the eastern slopes of mountains on all islands, where the trade winds dominate (e.g., the northeastern side of the Island of Hawai‘i). In general, these projections suggest the following:

» The dry areas of the islands will trend toward drier conditions in the future during both wet and dry seasons.

» The wet areas of the islands will trend toward small increases during the wet season.

Table 2-1. Downscaled climate projections

Dataset	Variables	Method	Spatial Resolution	Temporal Resolution	Time Periods	Ensemble	Scenarios	Considerations [25]
Statistical downscaling using a multiple linear regression method [22]	Precipitation	Statistical downscaling	0.5 min (1/120 degree)	Wet Season (November–April) Dry Season (May – October)	1975-2005 (baseline) 2041-2070 (~2050s) 2071-2100 (~2080s)	32 CMIP5 GCMs Results are provided as ensemble average	RCP4.5 RCP8.5	**Pros:** » Results for mid-century and end-of-century were obtained to capture different time horizons. » Ensemble of GCMs was considered to capture the range projected across a swath of models. » Results for a moderate scenario (RCP4.5) and high scenario (RCP8.5) were obtained to capture societal-based uncertainties. » Downscaling method can support the assessment of multiple climate simulations. **Cons:** » Seasonal results require a simplified scaling approach when considering changes in monthly and/or precipitation and temperature events. » Because of the PDO influence, statistical downscaling can be “trained” to simulate one long-term phenomena that may not be adequate for simulating different conditions. » Calibration of the dry season precipitation can be challenging because of lack of large-scale rainfall pattern data.

Dataset	Variables	Method	Spatial Resolution	Temporal Resolution	Time Periods	Ensemble	Scenarios	Considerations [25]
Hawai‘i Regional Climate Model Simulations (HRCM) [26]	Precipitation Temperature Wind Clouds Solar Radiation	Dynamical downscaling	1 km for Maui 3 km for other main islands	Monthly	1990-2009 (baseline) 2080-2099 (end-of-century)	HRCM is driven by the ensemble mean of 20 CMIP3 GCMs	A1B (refer to [27])	**Pros:** » Simulations adequately capture the westerly disturbances and tropical cyclones. **Cons:** » This work uses a pseudo-global warming downscaling method that may not account for synoptic-scale changes. » Intensive processing generally does not allow for multiple climate simulations.
Statistical method for high-resolution temperature projections [23]	Temperature	Statistical downscaling	100 m	Monthly	1976-2005 (baseline) 2040-2069 (~2050s) 2070-2099 (~2080s)	32 CMIP5 GCMs Results are provided as ensemble average and uncertainty range	RCP4.5 RCP8.5	**Pros:** » This work has similar pros to those of [**22**]. » Method considers an elevation-dependent amplification factor. **Cons:** » As the method relies on the change in temperature from surface to aloft (vertical gradient), it is unclear if additional feedbacks (e.g., heat-transport) need to be accounted for.

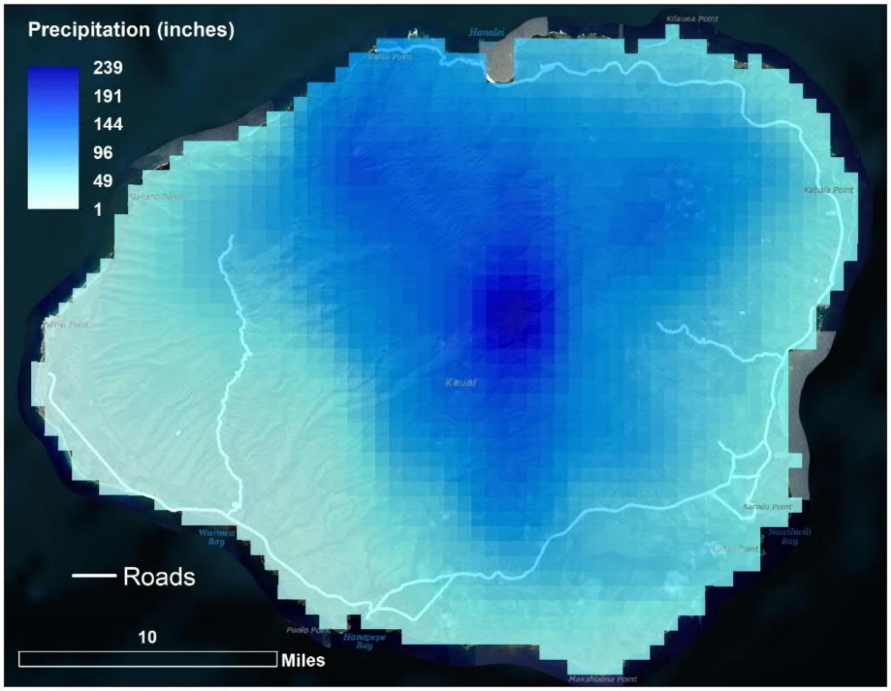

Figure 2-1. Historical precipitation values during the wet season for the Kaua'i District [24,1,2]

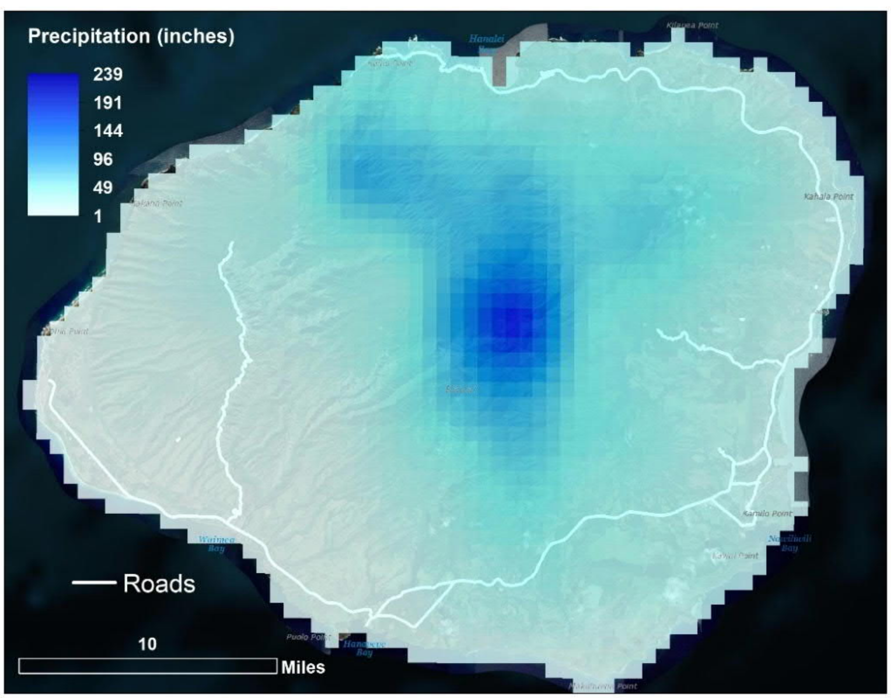

Figure 2-2. Precipitation values during the wet season in the middle of the century (RPC8.5 emissions scenario) for the Kaua'i District [22,24,1,2]

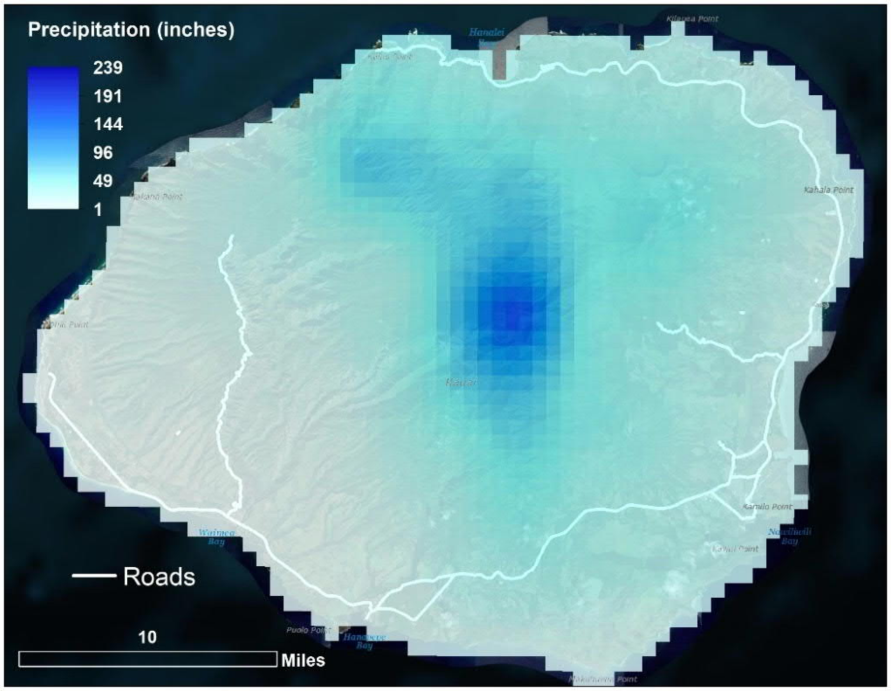

Figure 2-3. Precipitation values during the wet season at the end of the century (RPC8.5 emissions scenario) for the Kaua'i District [22,24,1,2]

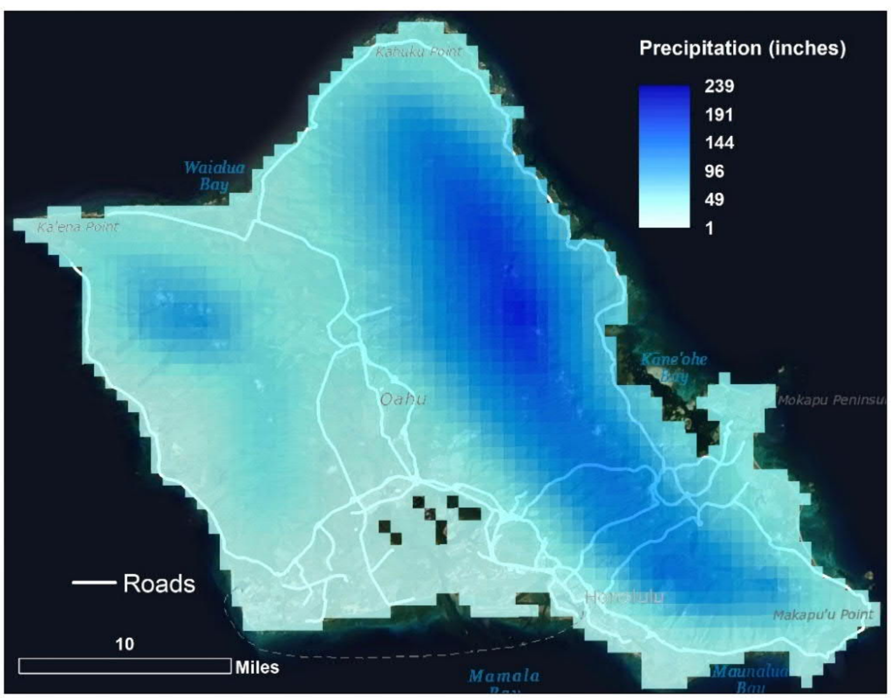

Figure 2-4. Historical precipitation values during the wet season for the O'ahu District [24,1,2]

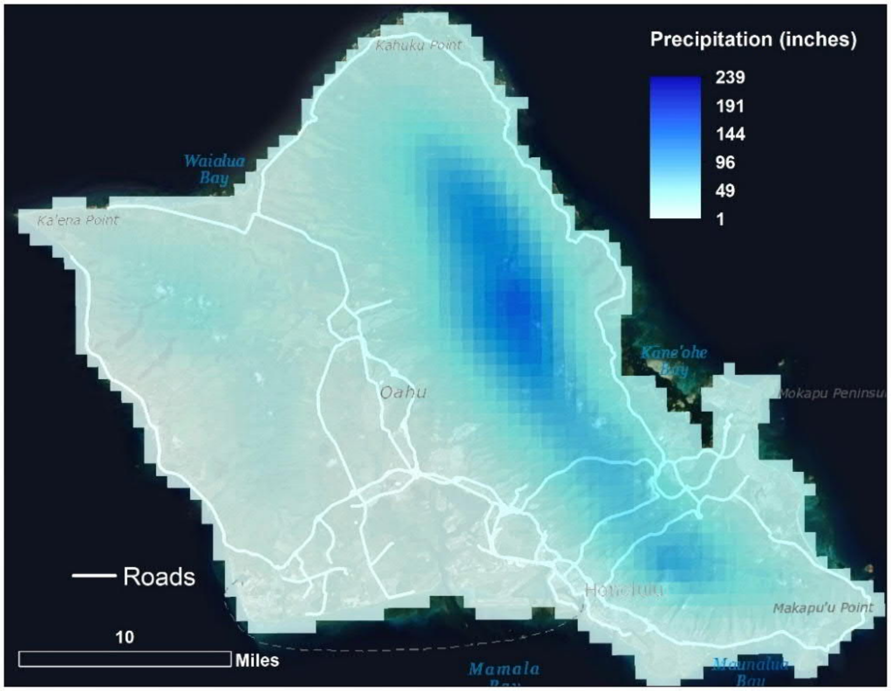

Figure 2-5. Precipitation values during the wet season in the middle of the century (RPC8.5 emissions scenario) for the O'ahu District [22,24,1,2]

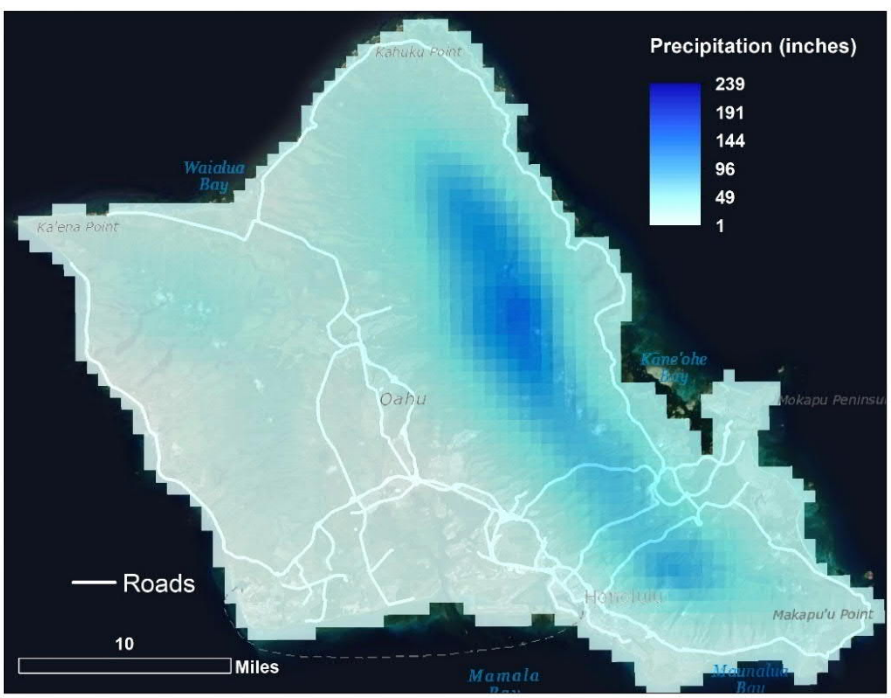

Figure 2-6. Precipitation values during the wet season at the end of the century (RPC8.5 emissions scenario) for the O'ahu District [22,24,1,2]

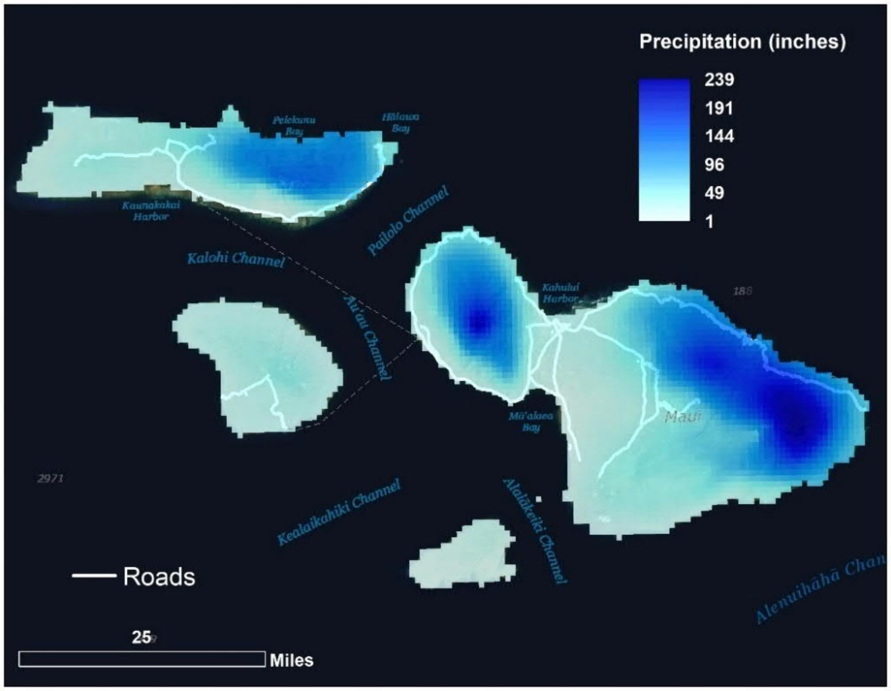

Figure 2-7. Historical precipitation values during the wet season for the Maui District [24,1,2]

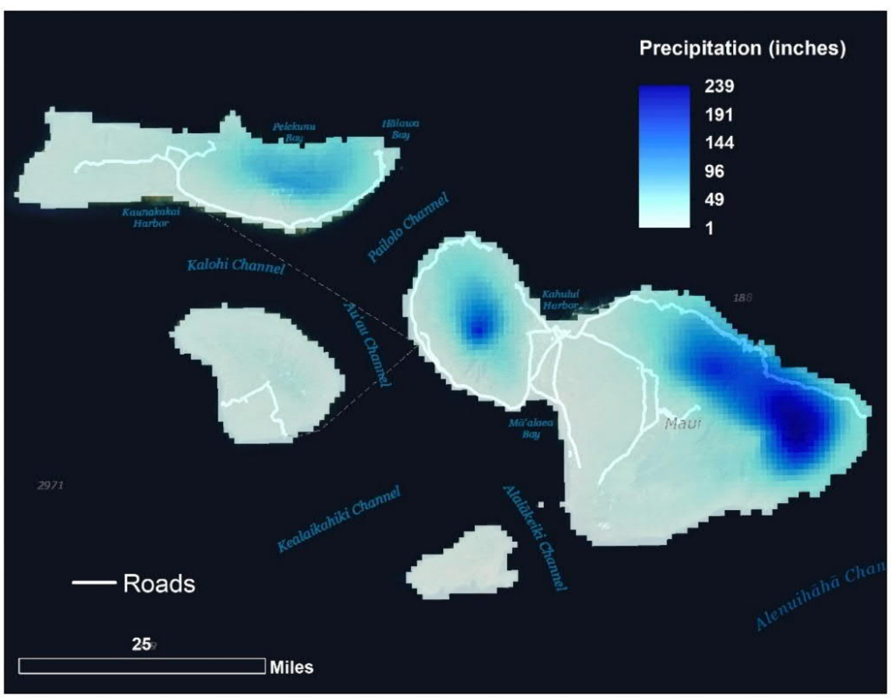

Figure 2-8. Precipitation values during the wet season in the middle of the century (RPC8.5 emissions scenario) for the Maui District [22,24,1,2]

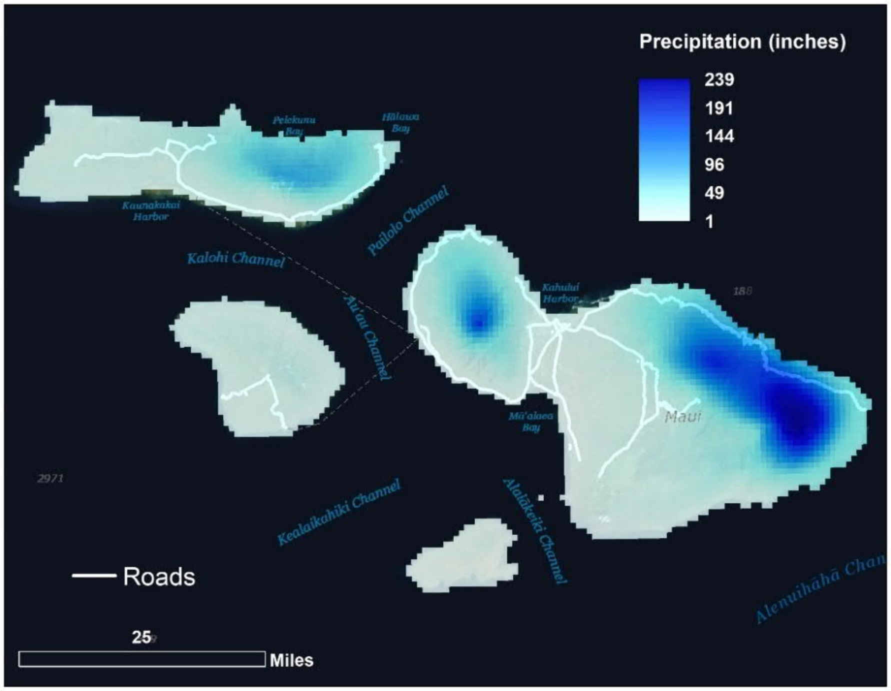

Figure 2-9. Precipitation values during the wet season at the end of the century (RPC8.5 emissions scenario) for the Maui District [22,24,1,2]

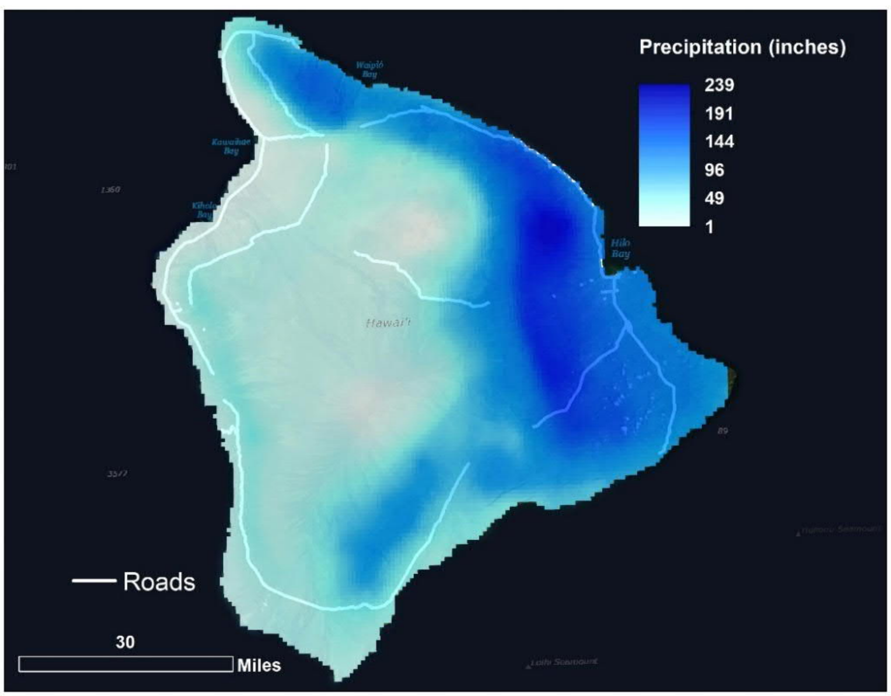

Figure 2-10. Historical precipitation values during the wet season for the Hawai'i District [24,1,2]

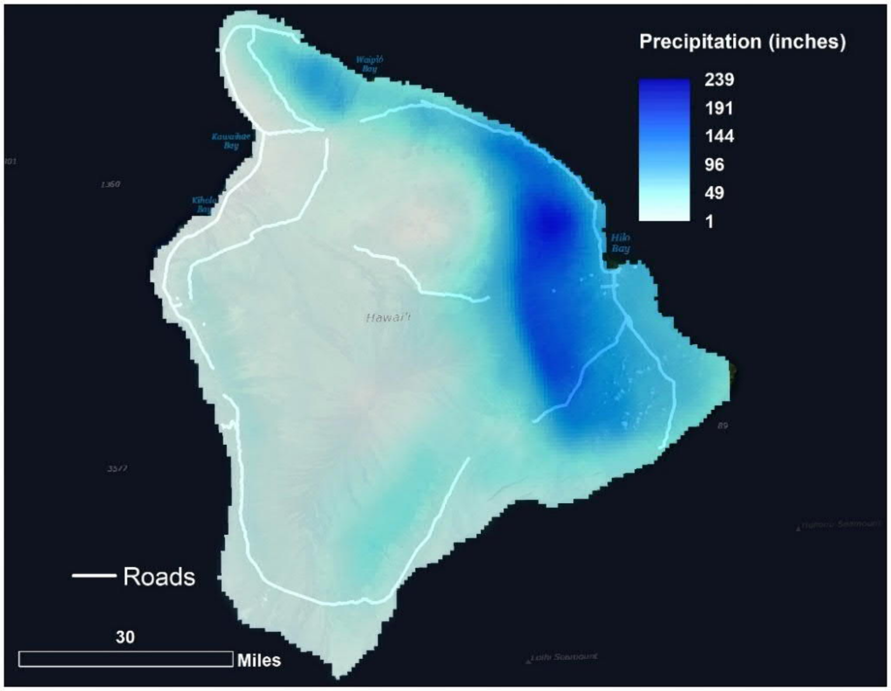

Figure 2-11. Precipitation values during the wet season in the middle of the century (RPC8.5 emissions scenario) for the Hawai'i District [22,24,1,2]

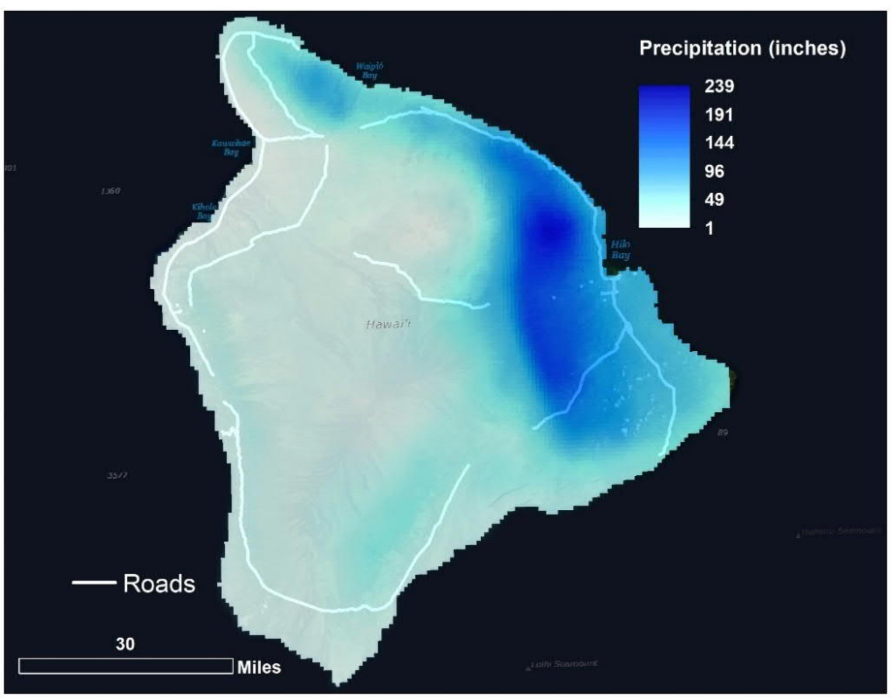

Figure 2-12. Precipitation values during the wet season at the end of the century (RPC8.5 emissions scenario) for the Hawai'i District [22,24,1,2]

2.5. TEMPERATURE

The analysis of temperature data was focused on understanding annual average changes. The future changes in temperature of [23] (i.e., the mean of the GCM ensemble and the corresponding 97.5th-percentile value, which represents a high-consequence, low-probability scenario) were added to the historical mean annual data [28] to obtain possible future temperature values. Figure 2-13 through Figure 2-24 illustrate part of the results. The data indicate that temperatures are projected to increase by the end-of-century, especially along the coastline, where HDOT roads tend to be located. In general, temperature change is expected to be larger at higher elevations. This may not be easily observed in the figures due to the lapse rate effect on the absolute temperature and the colder temperatures at higher elevations.

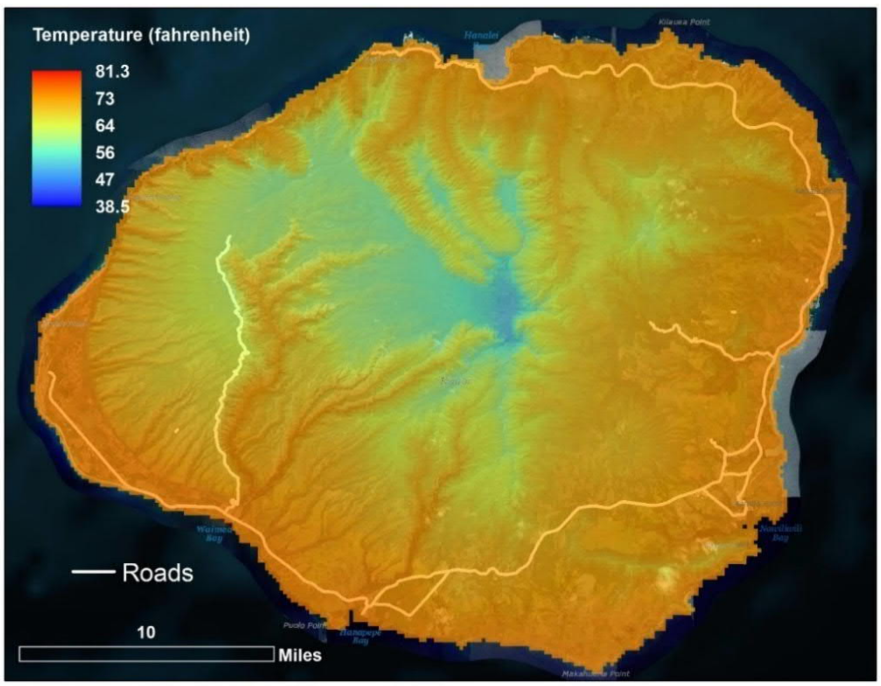

Figure 2-13. Historical annual mean temperature values for the Kaua'i District [28,1,2]

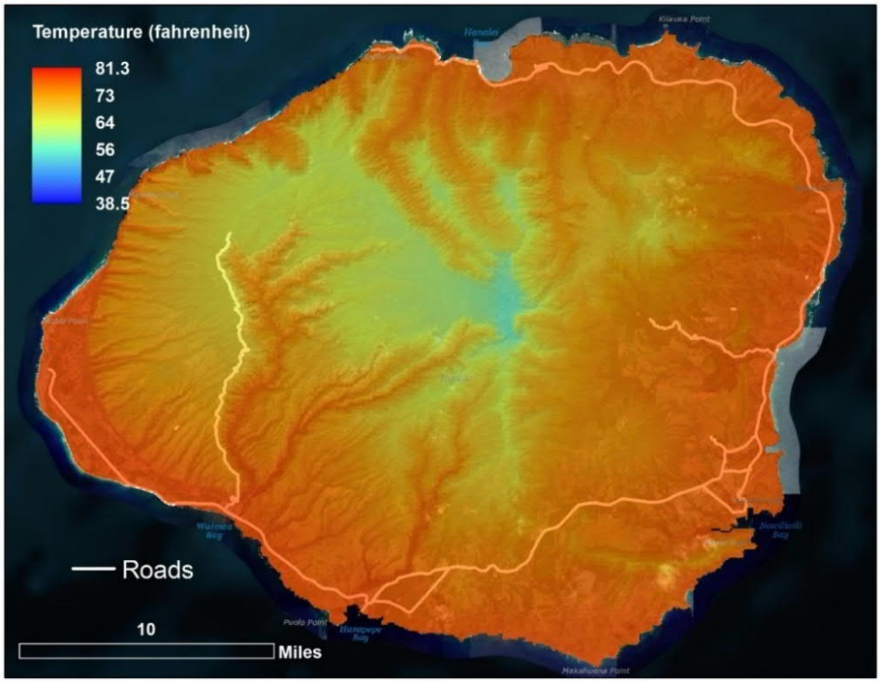

Figure 2-14. Annual mean temperature values in the middle of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the Kaua'i District [23,28,1,2]

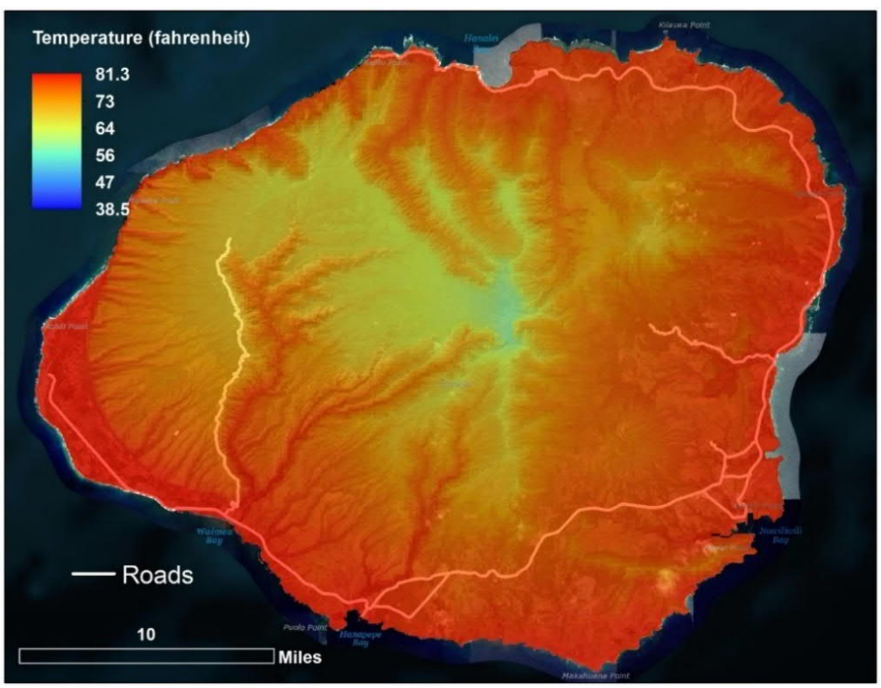

Figure 2-15. Annual mean temperature values at the end of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the Kaua'i District [23,28,1,2]

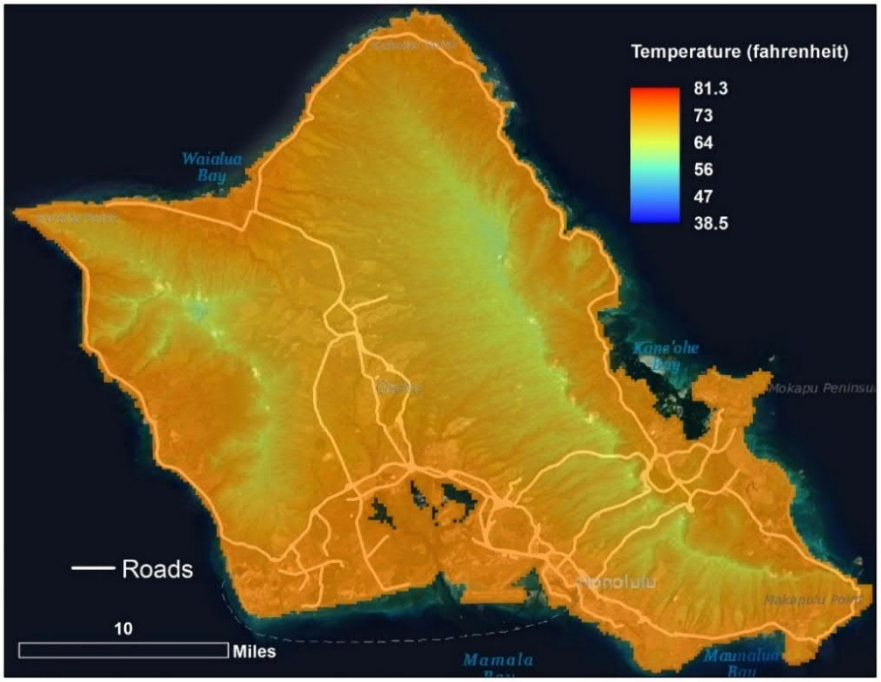

Figure 2-16. Historical annual mean temperature values for the O'ahu District [28,1,2]

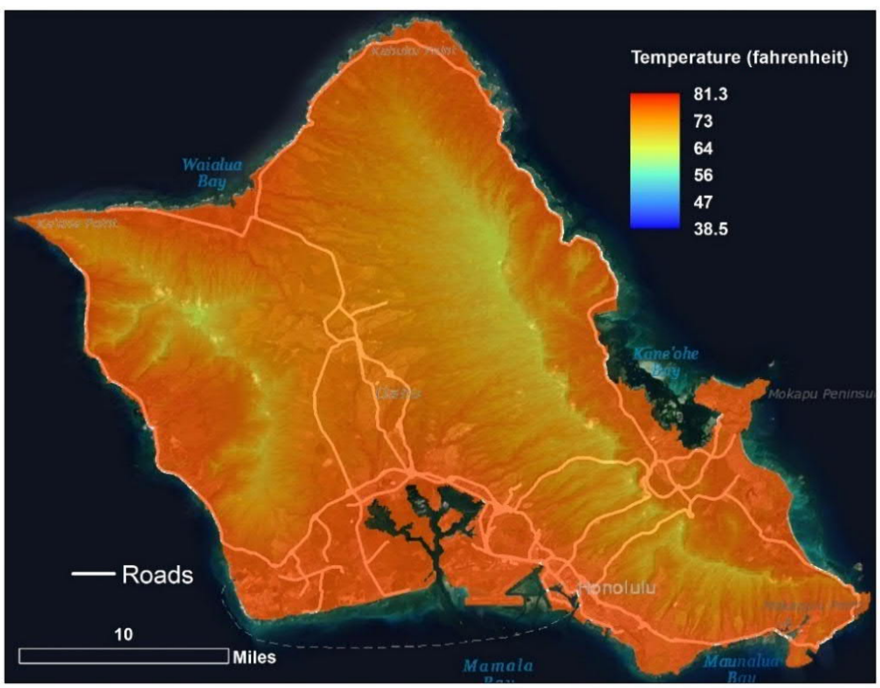

Figure 2-17. Annual mean temperature values in the middle of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for O'ahu District [23,28,1,2]

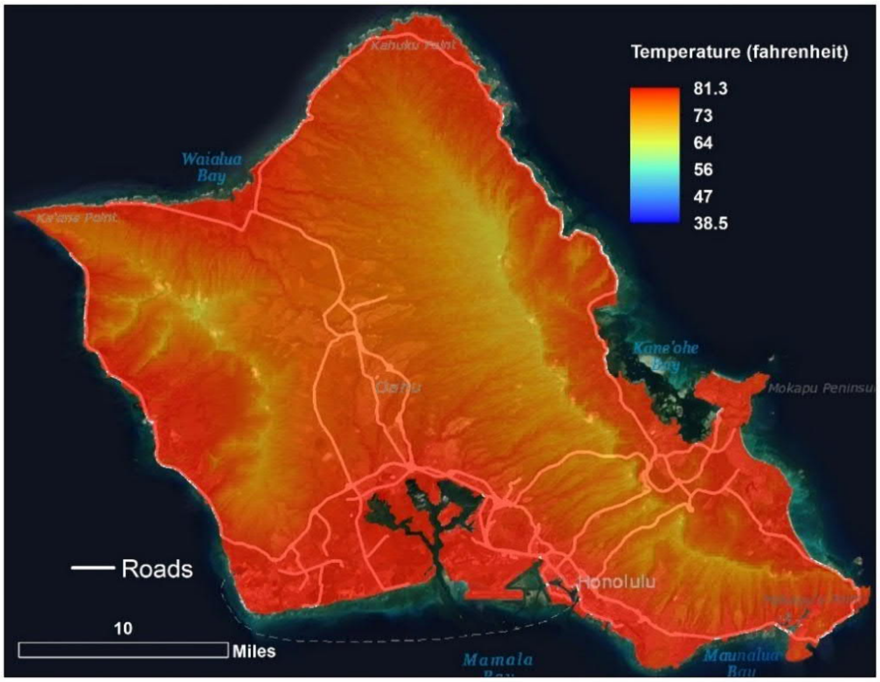

Figure 2-18. Annual mean temperature values at the end of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the Oʻahu District [23,28,1,2]

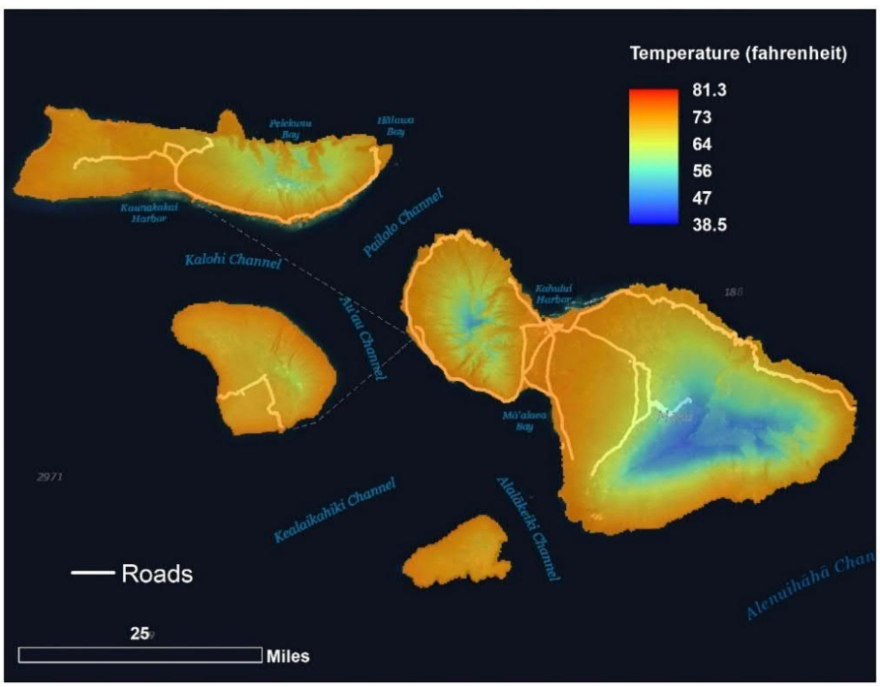

Figure 2-19. Historical annual mean temperature values for the Maui District [28,1,2]

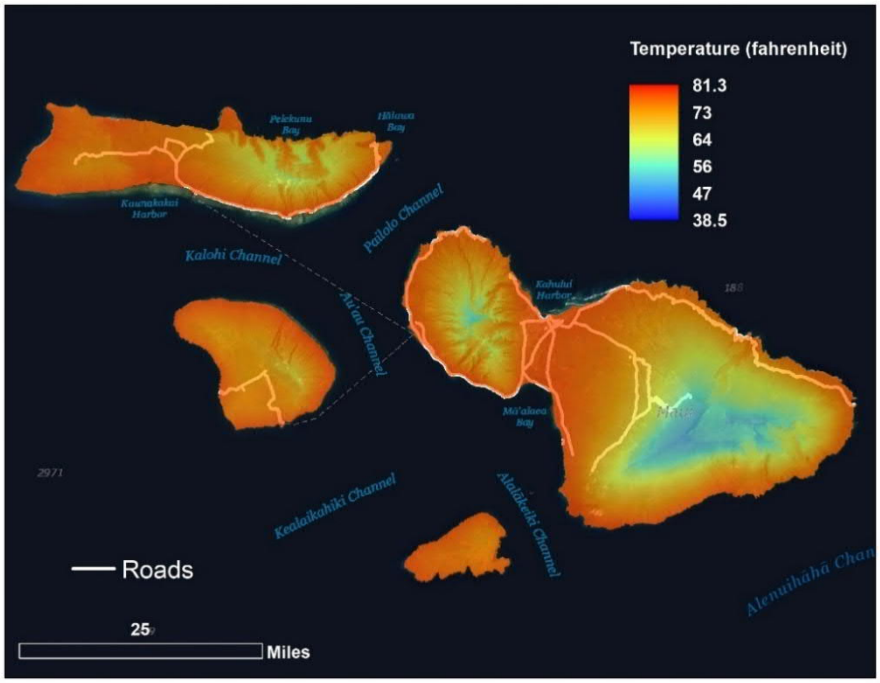

Figure 2-20. Annual mean temperature values in the middle of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the Maui District [23,28,1,2]

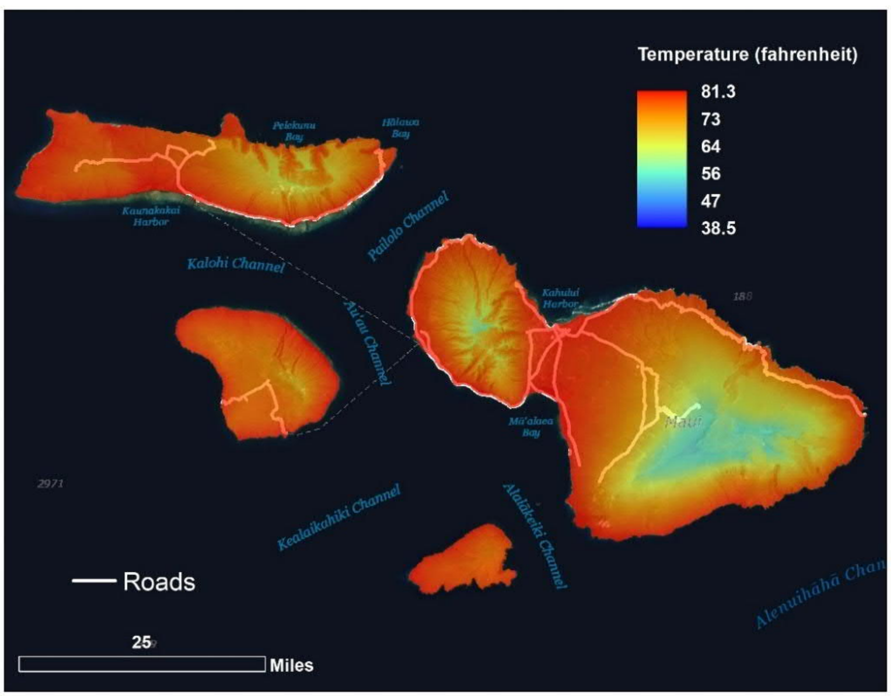

Figure 2-21. Annual mean temperature values at the end of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the Maui District [23,28,1,2]

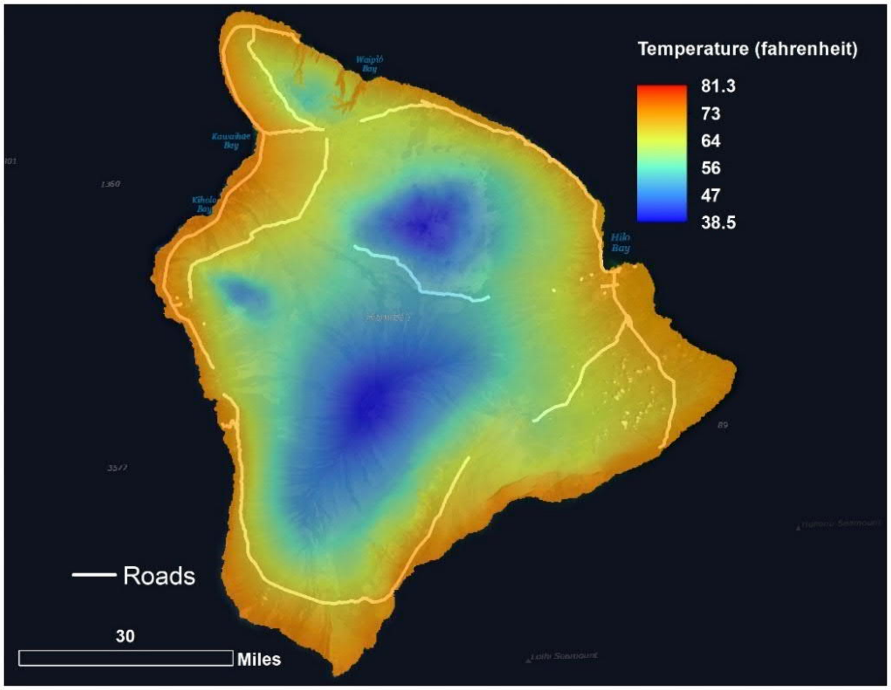

Figure 2-22. Historical annual mean temperature values for the **Hawai‘i** District [28,1,2]

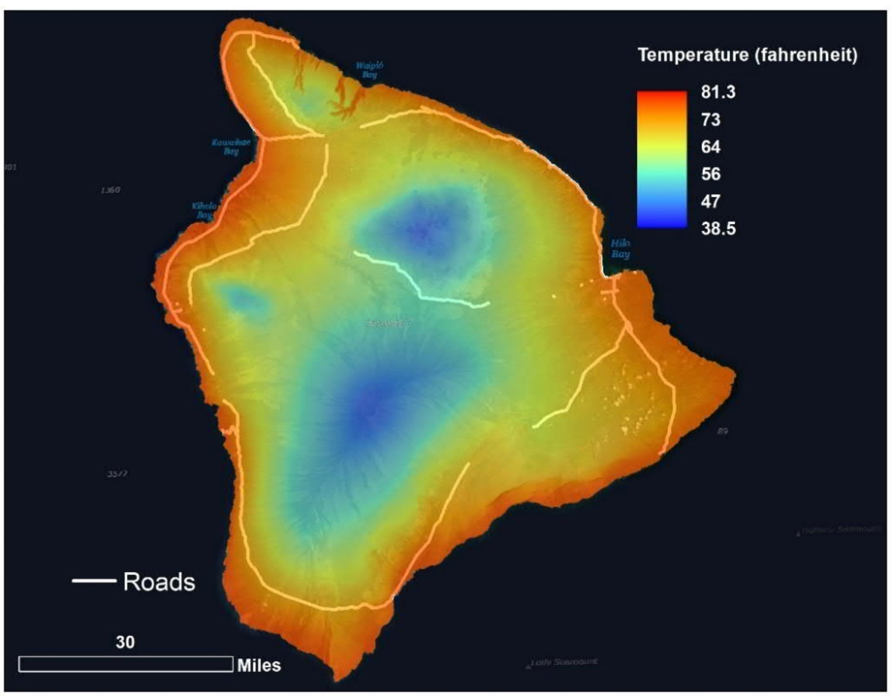

Figure 2-23. Annual mean temperature values in the middle of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the **Hawai‘i** District [23,28,1,2]

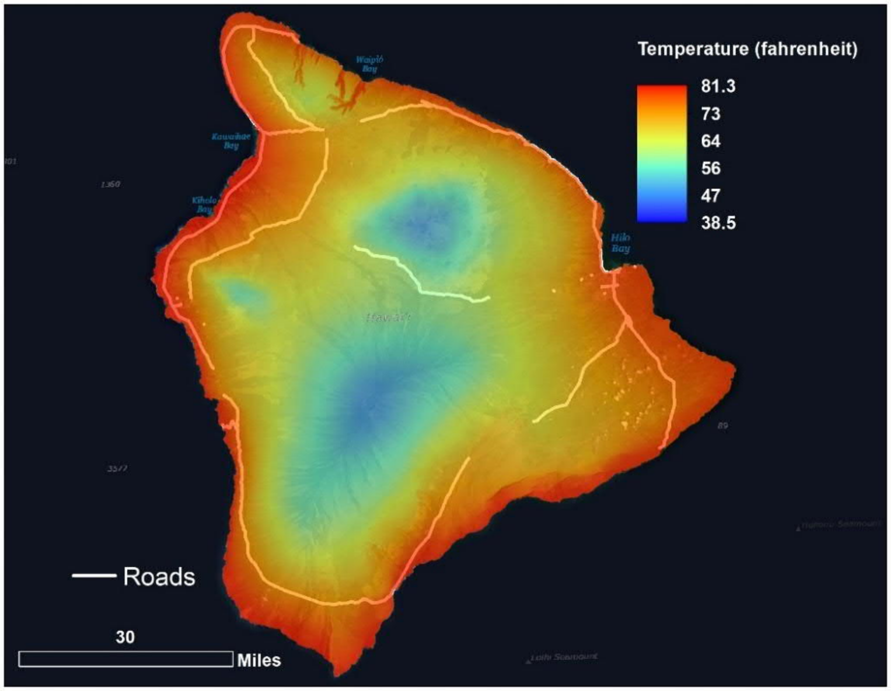

Figure 2-24. Annual mean temperature values at the end of the century (RPC8.5 emissions scenario, 97.5th-percentile of climate model ensemble results) for the Hawai'i District [23,28,1,2]

2.6. RECOMMENDATIONS TO IMPROVE CLIMATE PROJECTION DATA

» **Recommendation 2-1.** Precipitation and temperature data at the available temporal scale (i.e., annual, seasonal) cannot be used for the assessment of hazard events. A refined temporal resolution (i.e., daily) is needed. The development of data at this refined resolution is an active area of research. Three research efforts that may contribute to the generation of these data are underway:

- o the dynamical downscaling of climate data using the Weather Research and Forecasting (WRF) model [29] for additional time horizons and WCRP CMIP5 GCM outputs,
- o the role of PDO and anthropogenic climate change on determining near-term rainfall and temperature projections [30], and
- o the development of enhanced statistical methods that also consider precipitation events.

HDOT should engage with these research efforts and monitor the availability of new climate projection data. On the one hand, dynamical downscaling methods using WRF can readily provide daily resolved weather and climate data for precipitation, temperature, and other variables. However, the computational cost and storage of the data are expensive, and thus only a few scenarios and short time intervals have been produced so far. On the other hand, the statistical downscaling is often associated with long development times (data acquisition, processing, tuning of the model parameters, and cross-validation), and hence, may reach limits in applications to data with high temporal resolution. Precipitation and temperature projection data should be obtained by climate simulation (i.e., climate model run under a given future scenario) to ensure that these data represent physically plausible futures. Corresponding statistical descriptors of GCM ensembles are only meant to provide points of reference in the distribution of physically plausible climate projection values.

» **Recommendation 2-2.** HDOT should assess the impact of diurnal temperature changes in the hottest month of the year and future extreme heat on the quality of pavement. Effects such as pavement buckling would lead to increased repair and maintenance costs. HDOT may seek a partnership with the University of Hawaiʻi at Mānoa's pavement engineering research group.

CHAPTER 3. **ROCKFALL AND LANDSLIDE EXPOSURE ASSESSMENT**

3.1. PREVIOUS WORK AND EXISTING DATA

HDOT manages the Rockfall Protection Program, which is focused on the statewide analysis of road sections that may be affected by rockfalls and landslides and their prioritization for mitigation measures [31,32]. Prioritization decisions are supported by an adapted version of the Federal Highway Administration (FHWA) Rockfall Hazard Ranking System [33]. The ranking system considers geotechnical parameters such as slope height and angle, structural condition, rock friction, difference in erosion rates, erosion features, and block size. The ranking system also considers climate and the presence of water on slopes along with the frequency of past events (i.e., rockfall history).

The USGS landslide susceptibility maps for Hawaiʻi [34] identify, at a high level, steep areas where rockfalls and landslides may occur. The susceptibility categories represent ranges of calculated Factors of Safety (FOS) [35]. These factors were obtained using a methodology [36] that included a one-dimensional, infinite slope-stability model, a DEM of 10-meter resolution, and expert-estimated values for rock and soil shear strengths. This method made the following simplifying assumptions: (1) the average soil depth is 2 meters across all islands, (2) groundwater flow is parallel to the ground surface, (3) each DEM cell moves as a rigid block, and (4) the stability of each cell is independent of the surrounding cells [36]. This method can be used as a rapid assessment to identify areas where rockfalls and landslides may occur, and should be modified in future studies by detailed field investigations and adjustments for site-specific conditions. The relationships between susceptibility categories and FOS are presented in Table 3-1. Other susceptibility classification methods previously used in Hawaiʻi are qualitative, and, therefore, of limited applicability (e.g., [37]).

Table 3-1. Susceptibility categories and corresponding FOS [35]

Susceptibility categories	Factor of Safety
Moderate	2.01 – 3.5
High	1.51 – 2.0
Very high	Less than 1.5

3.2. METHODOLOGY FOR EXPOSURE ASSESSMENT

The methodology used in this exposure assessment was focused on first assigning (1) the data of the Rockfall Protection Program, specifically those of priority sites (i.e., class A as described in [32]), and (2) the susceptibility categories [34] to road segments to understand the spatial distribution of rockfall and landslide hazards throughout the State. The highest susceptibility category within a 0.1-mile radius (approximately 530 feet) of a road segment was assigned to that segment. This assignment combined geomorphic and slope-stability data with the historical incidence of rockfall and landslide hazards, leading to the identification of areas prone to future instability.

Future precipitation available for Hawaiʻi has a coarse resolution (refer to Chapter 2 for more information) and, therefore, has a limited application in understanding possible future rockfall and landslide events. Changes in future precipitation can still be used to understand overall changes expected in slope stability.

To obtain possible future precipitation values, anticipated percent changes of the wet-season precipitation values of [22] were applied to present precipitation values represented by National Oceanic and Atmospheric Administration (NOAA) Atlas 14 [38,39] 24-hour precipitation depths for a 100-year return period event (median values of the precipitation-return period relationship and the corresponding upper limit values of the 90-percent confidence intervals). The percent changes of the wet-season precipitation values were available for two time horizons (i.e., mid-century and end-of-century) and two warming scenarios (i.e., moderate warming or RCP4.5 and high warming or RCP8.5). A major assumption of this application is that shifts in seasonal precipitation are representative of projected shifts in daily precipitation (refer to [40]). Although there is precedence for this approach, particularly in regions that are extremely challenging to project daily rainfall events, such as in Hawaiʻi, this approach is coarse and does not support a precise application of the results. As data of improved resolution become available (refer to the recommendations in Section 2.6), this approach should be revised.

Once estimated, present and possible future precipitation values were assigned to each road segment. The precipitation values assigned to each segment were the maximum values at the locations of highest susceptibility category within a 0.1-mile radius of the segment. It is worth noting that road segments that were not considered a priority in the Rockfall Protection Program or without a landslide susceptibility category were not assigned a precipitation value.

3.3. RESULTS OF EXPOSURE ASSESSMENT

The results of the rockfall and landslide exposure assessment are shown in Figure 3-1 through Figure 3-8 and include two maps for each District illustrating the density of road segments with high and very high susceptibility within a 1-square-kilometer area (approximately 0.4 square mile). Low density indicates a small number of segments in an area, and high density indicates a large number of segments in an area. For each District, the first map shows road segments that have been identified as priority sites in the Rockfall Protection Program, and the second map shows segments that have not been prioritized or are not in the Program. Therefore, for each District, the second map displays areas that may need to be considered in the Rockfall Protection Program in the future, either as priority sites or as new sites, or areas that may need to be reassessed (e.g., a site of concern may need to be extended to include adjacent segments). By District, some examples of the areas that may need to be considered include the following:

- Kauaʻi District (Figure 3-2): along Kūhiō Highway near Wainiha in North Kauaʻi
- Oʻahu District (Figure 3-4): along Farrington Highway near Mākua Beach and Nānākuli, along Pali Highway mauka of Kāneʻohe and Kailua, and along Kalanianaʻole Highway in Waimānalo
- Maui District (Figure 3-6): along the Hāna Highway in East Maui, especially near Wailua, and portions of Honoapiʻilani Highway on West Maui
- Hawaiʻi District (Figure 3-8): portions of Māmalahoa Highway on Hamakua Coast

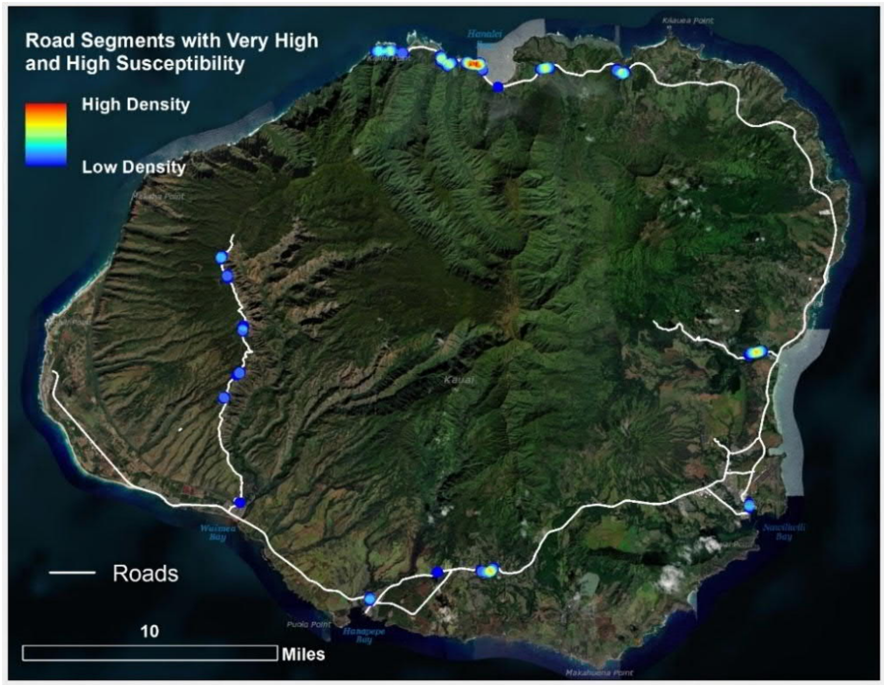

Figure 3-1. State road segments in the Kauaʻi District prioritized in the HDOT Rockfall Protection Program with USGS high and very high landslide susceptibility [32,34,1,2]

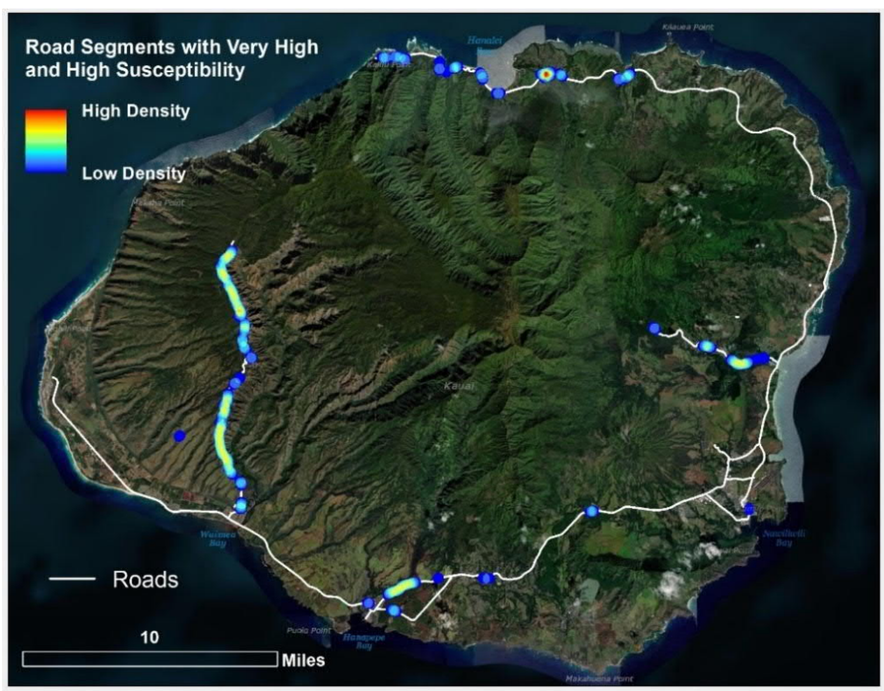

Figure 3-2. State road segments in the Kauaʻi District not prioritized in the HDOT Rockfall Protection Program (or not in the program) with USGS high and very high landslide susceptibility [34,1,2]

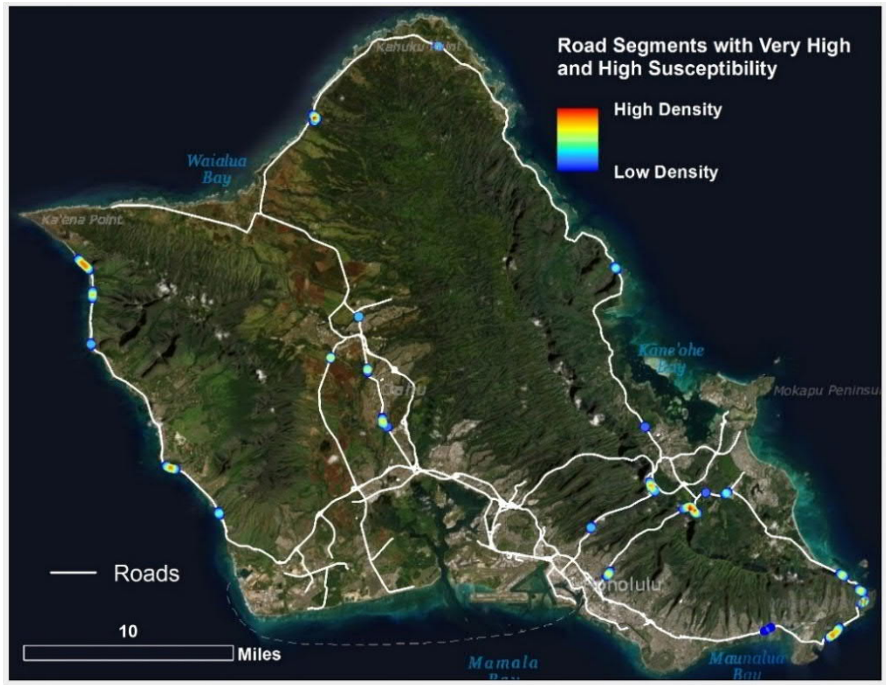

Figure 3-3. State road segments in the Oʻahu District prioritized in the HDOT Rockfall Protection Program with USGS high and very high landslide susceptibility [32,34,1,2]

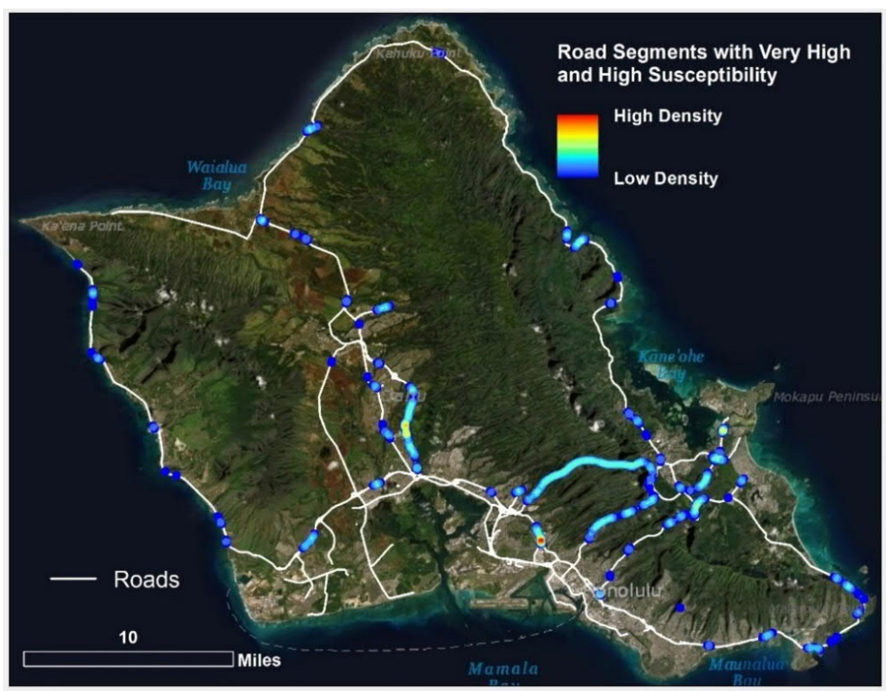

Figure 3-4. State road segments in the Oʻahu District not prioritized in the HDOT Rockfall Protection Program (or not in the program) with USGS high and very high landslide susceptibility [34,1,2]

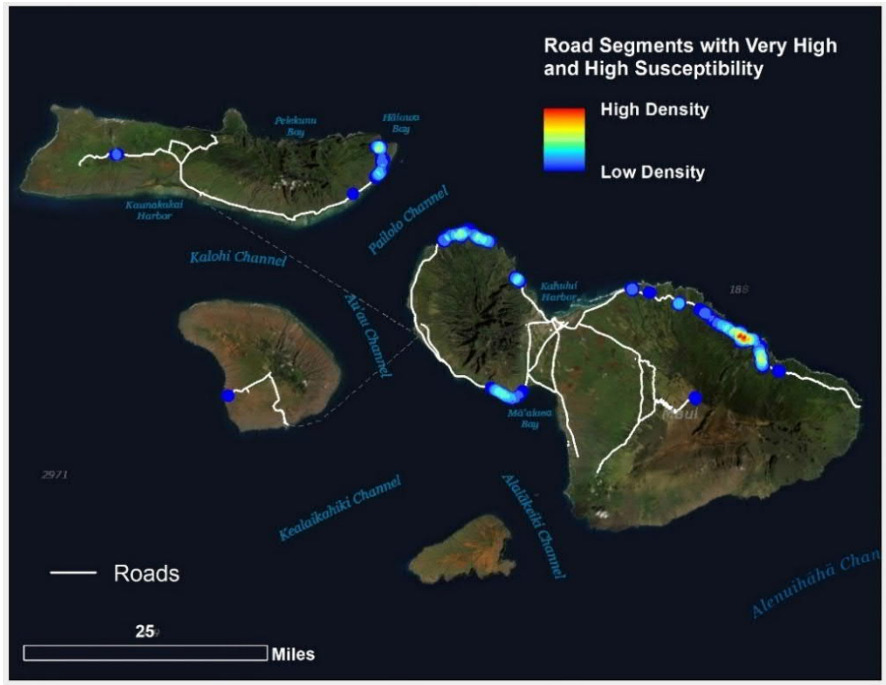

Figure 3-5. State road segments in the Maui District prioritized in the HDOT Rockfall Protection Program with USGS high and very high landslide susceptibility [32,34,1,2]

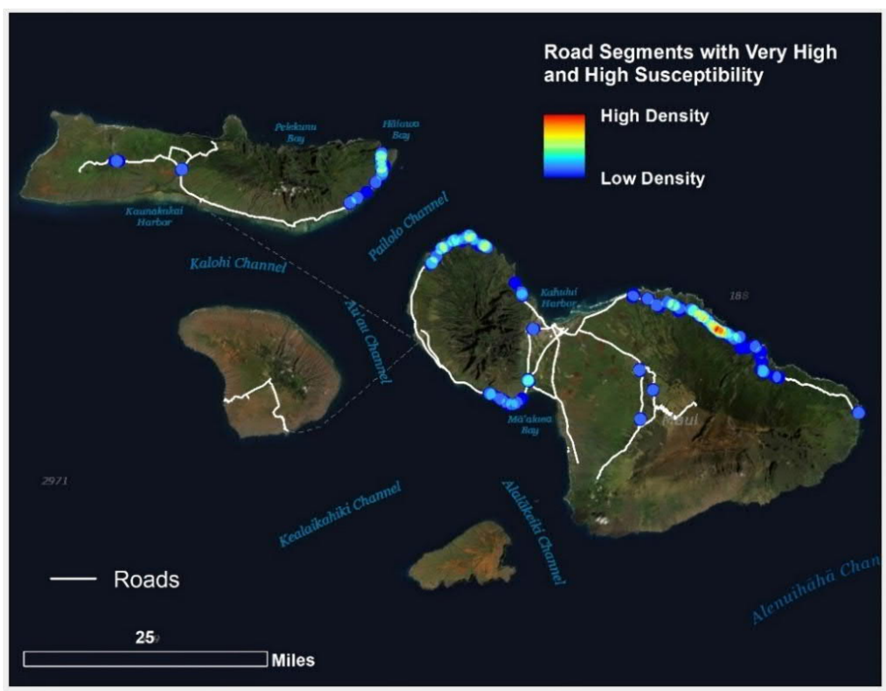

Figure 3-6. State road segments in the Maui District not prioritized in the HDOT Rockfall Protection Program (or not in the program) with USGS high and very high landslide susceptibility [34,1,2]

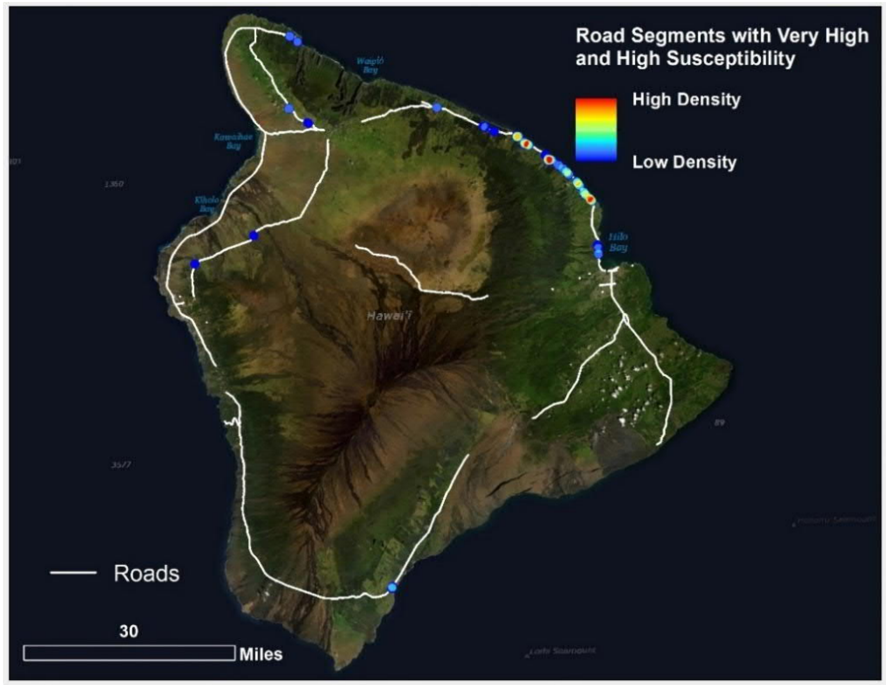

Figure 3-7. State road segments in the Hawai'i District prioritized in the HDOT Rockfall Protection Program with USGS high and very high landslide susceptibility [32,34,1,2]

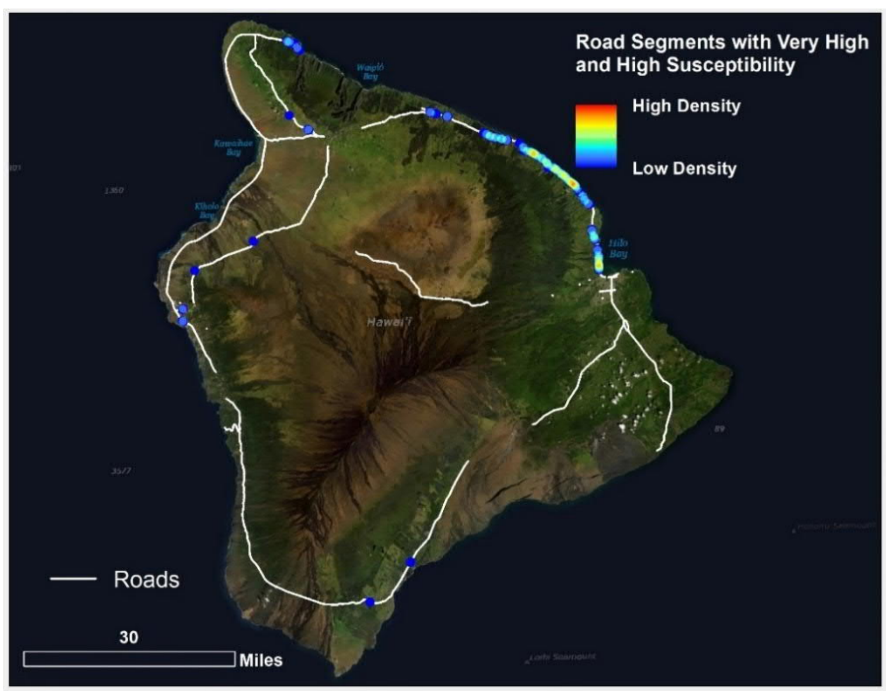

Figure 3-8. State road segments in the Hawai'i District not prioritized in the HDOT Rockfall Protection Program (or not in the program) with USGS high and very high landslide susceptibility [34,1,2]

Due to the high-level resolution of this study, the second map may also display segments that would not require a mitigation or control measure such as elevated segments along highways, which do not abut slopes on either side of the roadway travel lanes. Therefore, these results need to be further evaluated through field visits.

Additionally, the number of miles of priority road segments in the Rockfall Protection Program was plotted against assigned present, mid-century, and end-of-century precipitation values (refer to Section 3.2). Figure 3-9 shows the number of miles of road segments with priority rockfall/landslide sites of large block size (i.e., more than 3 feet) or volume (i.e., more than 9 cubic yards) and their assigned present and future precipitation values for a maximum 24-hour event of a 100-year return period during the wet season considering a high warming scenario and the upper limit values of the 90-percent confidence intervals of the precipitation-return period relationship. Figure 3-10 shows a similar relationship between the number of miles of road segments with priority rockfall/landslide sites of high event frequency (i.e., many falls and constant falls) and precipitation values. Large block size or volume and high frequency are attributes that characterize sites of high concern. The results indicate that the anticipated increase in overall precipitation may impact 25% of road segments with priority rockfall/landslide sites of large block size or volume by the middle of the century through the end-of-century, and 46% of road segments with priority rockfall/landslide sites of high event frequency by the middle of the century through the end-of-century. Exposure assessment results are also summarized by District in Table 3-2 and Table 3-3.

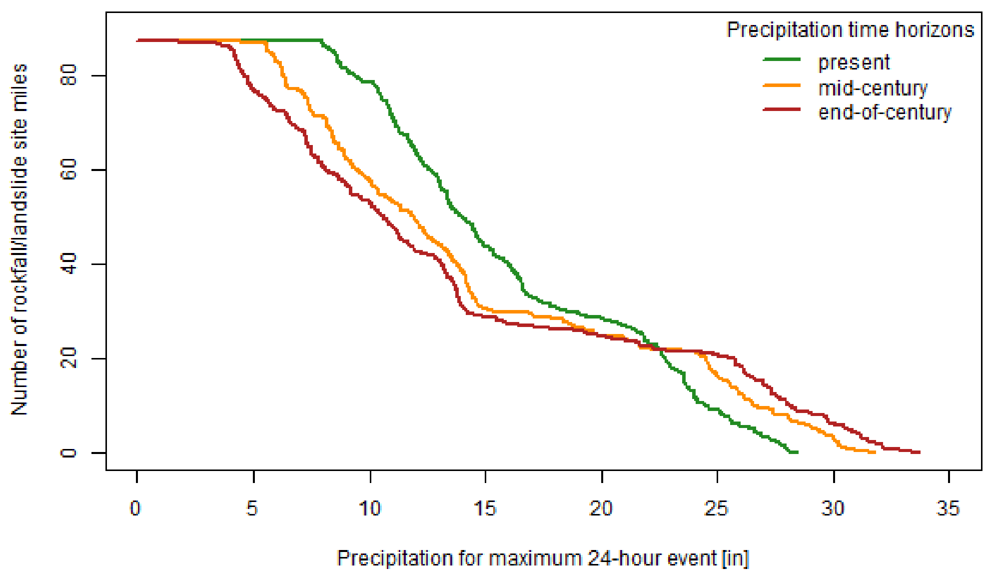

Figure 3-9. Estimated number of rockfall/landslide site miles with large block size (i.e., more than 3 feet) or volume (i.e., more than 9 cubic yards) associated with a certain precipitation level or higher[32]

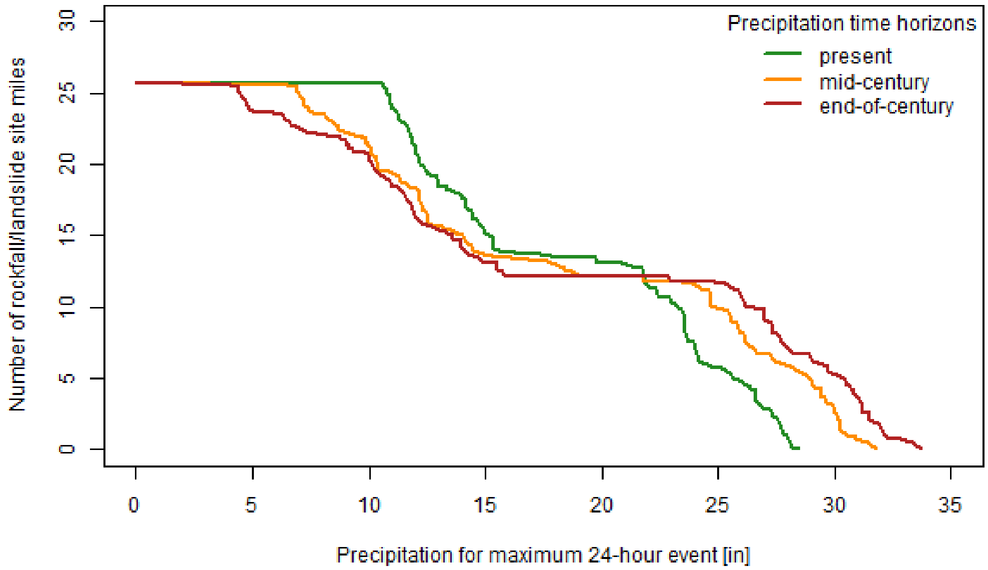

Figure 3-10. Estimated number of rockfall/landslide site miles with high event frequency (i.e., many falls and constant falls) associated with a certain precipitation level or higher[32]

Table 3-2. Distribution of State roads, bridges, culverts, and tunnels exposed to rockfall and landslide hazard by inclusion on the Rockfall Protection Program [1,3,5]

District	Rockfall Protection Program (class A)	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kaua'i	Excluded	94.7	35	7	0
	Included	8.6	9	0	0
O'ahu	Excluded	277.5	158	19	4
	Included	11.7	16	0	1
Maui	Excluded	203.4	70	10	0
	Included	39.8	27	1	1
Hawai'i	Excluded	301.9	56	34	0
	Included	33.6	26	2	0
All Districts	Excluded	877.5	319	70	4
	Included	93.7	78	3	2

3.4. RECOMMENDED ACTIONS FOR HIGHWAYS

» **Recommendation 3-1.** HDOT should evaluate the need to prioritize additional rockfall/landslide sites in its Rockfall Protection Program (e.g., sites associated with high or very high susceptibility and areas of increased precipitation), include additional sites, or extend current sites in the program.

- **Recommendation 3-2.** HDOT should consider the susceptibility values and precipitation estimations used in this assessment in future prioritizations of sites in its Rockfall Protection Program, understanding the limitations of these datasets. Investments in slope-stability mitigation can be prioritized for the following areas, subject to confirmation of localized conditions (e.g., mitigation works may already be in place in several locations):
  - Sites associated with high or very high susceptibility, especially if these sites are associated with areas of increased precipitation
  - Sites of large block size or volume, or of high event frequency, and associated with areas of increased precipitation
- **Recommendation 3-3.** HDOT should identify and evaluate the performance of culverts in areas that will experience an increase in precipitation to address the adequacy of their drainage capacity. Poorly performing culverts could cause water retention along roadways that leads to slope saturation and potential increases of instability.

Table 3-3. Distribution of State roads, bridges, culverts, and tunnels exposed to rockfall and landslide hazard by susceptibility category [1,3,5]

District	Susceptibility Category	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	Excluded	60.2	22	3	0
	Moderate	24.5	12	3	0
	High	15.4	10	1	0
	Very high	3.3	0	0	0
Oʻahu	Excluded	195.6	113	11	0
	Moderate	54.7	34	3	0
	High	34.7	22	5	1
	Very high	4.2	5	0	4
Maui	Excluded	142.5	27	8	0
	Moderate	57.9	32	1	0
	High	37.2	30	2	1
	Very high	5.6	8	0	0
Hawaiʻi	Excluded	258.1	18	31	0
	Moderate	54.6	26	4	0
	High	14.1	22	1	0
	Very high	8.7	16	0	0
All Districts	Excluded	656.4	180	53	0
	Moderate	191.7	121	14	0
	High	101.4	67	6	2
	Very high	21.8	29	0	4

3.5. IMPROVEMENTS TO DATA AND MODELS TO ASSESS RESILIENCE OF SYSTEM

- **Recommendation 3-4.** HDOT should support research efforts focused on detailed precipitation modeling (e.g., short duration-high intensity events) that builds upon the recommendations outlined in Chapter 2. These studies would support the evaluation of precipitation intensity-duration distributions and their anticipated changes due to climate change, informing future slope-stability assessments. Special structures such as bridges, culverts, and tunnels can benefit from improved assessments to determine actual exposure to rockfalls and landslides.
- **Recommendation 3-5.** In the meantime, HDOT should implement a remote, real-time slope monitoring program for priority sites, especially those sites that are difficult to access, to provide early warning of movement prior to rockfall and landslide events.

CHAPTER 4. CHRONIC COASTAL FLOODING EXPOSURE ASSESSMENT

4.1. PREVIOUS WORK AND EXISTING DATA

The Hawaiʻi Sea Level Rise Vulnerability and Adaptation Report [41,42] (hereafter referred to as the Report in this chapter) made available data that could be used to determine the exposure of roads to chronic coastal flooding related to anticipated levels of sea rise (i.e., 0.5, 1.1, 2.0, and 3.2 feet of global mean sea level rise), specifically marine inundation, groundwater inundation, annual high wave flooding, and coastal erosion. In accordance with the Intergovernmental Panel on Climate Change (IPCC) [43], the work in the Report associated 0.5, 1.1, 2.0, and 3.2 feet of global mean sea level rise with the estimated sea level rise mean values plus one standard deviation for the years 2030, 2050, 2075, and 2100, respectively, when assuming a high warming scenario (i.e., RCP 8.5). However, more recent work, specifically that of Sweet et al. [44], indicates that such levels of sea rise could be observed much earlier, especially once ice-sheet modeling is considered in future sea level rise estimates. This leads to the recommendation to use high sea level rise estimates in public policy and planning applications, especially those related to critical infrastructure, including highways. Such a recommendation has been documented in State guidance soon to be released [45].

The Statewide Coastal Highway Program Report [46,47] is a relatively new study that considers the work of Sweet et al. [44] in identifying road assets that could be inundated due to sea level rise. In the work of Francis et al. [46], inundation scenarios are explored in terms of deterministic levels of sea rise (i.e., 1, 2, and 3 feet) and probabilistic levels of sea rise for selected years (i.e., median sea level rise estimations for six climate scenarios and the years 2050 and 2100). While this new work may influence future State and local applications, the Report is the main reference used in planning guidance documents (e.g., [48,49]), and has been used in past exposure, vulnerability, and risk evaluations (e.g., [50,51,52]). One important aspect of the Report is the availability of estimations for groundwater inundation and the distinction between this inundation and marine inundation. Groundwater inundation can impact pavement quality and other ground conditions important for infrastructure development. Recent groundwater inundation work for Hawaiʻi has been documented in several reports (e.g., [53,54,55]).

4.2. METHODOLOGY FOR EXPOSURE ASSESSMENT

The data in the Report was used to identify areas exposed to four distinct hazards related to sea level rise: marine inundation, groundwater inundation, annual high wave flooding, and coastal erosion from non-exposed areas. No inundation depth values were available, leading to the assumption in this current work that if an area showed as inundated, then all assets contained in that area were assumed to be inundated as well.

In the Report, the methodology assumed that areas located below sea level and whose surfaces were connected to the ocean were vulnerable to marine flooding while all areas with elevations lower than sea level were vulnerable to groundwater inundation. In consequence, the methodology assumed that the hydraulic gradient was flat, resulting in an underestimation of groundwater inundation. Both marine flooding and groundwater inundation are referred to as passive flooding in the Report, and therefore, in this assessment. This dataset was available for all islands.

In contrast, datasets for annual high wave flooding and coastal erosion were only available for the islands of Kauaʻi, Oʻahu, and Maui due to limited historical information and geospatial data, excluding the islands of

Molokaʻi, Lānaʻi, and Hawaiʻi. This means that the exposure of 41% of the road segments, 25% of the bridges, and 51% of the culverts in the State could not be determined against these hazards (assets are shown as undetermined in the tables and figures in Section 4.3).

In addition to studying all four sea level rise hazards individually, the work of the Report combined these hazards into a single dataset referred to as sea level rise exposure area (i.e., SLR-XA) with the understanding that the areas identified in the tables and figures in Section 4.3 for Molokaʻi, Lānaʻi, and Hawaiʻi reflect only passive flooding (i.e., marine and groundwater inundation).

4.3. RESULTS OF EXPOSURE ASSESSMENT

Only the exposure associated with the 3.2-feet sea level rise scenario are illustrated here since this scenario is considered important for State and local policies and plans, although, as suggested by others (e.g., [46,48]), higher sea level rise estimations may now be more appropriate. The results by District for the 3.2-feet sea level rise scenario are presented in Table 4-1 through Table 4-4 and Figure 4-1 through Figure 4-4 (for illustration purposes, only road segments exposed to available sea level rise hazards, i.e., road segments in SLR-XA, are shown in the figures).

Table 4-1. Distribution of State roads, bridges, culverts, and tunnels exposed to passive flooding [42,1,3,5]

District	Passive flooding	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	Marine	1	25	1	0
	Groundwater	0.01	0	0	0
	Marine and groundwater	0	0	0	0
	None	102.3	19	6	0
Oʻahu	Marine	3.5	42	2	0
	Groundwater	1.1	9	2	0
	Marine and groundwater	0.03	4	0	0
	None	284.6	119	15	5
Maui	Marine	3.2	6	2	0
	Groundwater	0.2	0	0	0
	Marine and groundwater	0	0	0	0
	None	239.7	91	9	1
Hawaiʻi	Marine	0.3	6	0	0
	Groundwater	0	0	0	0
	Marine and groundwater	0	0	0	0
	None	335.2	76	36	0
All Districts	Marine	8	79	5	0
	Groundwater	1.3	9	2	0
	Marine and groundwater	0.03	4	0	0
	None	962	305	66	6

Table 4-2. Distribution of State roads, bridges, culverts, and tunnels exposed to annual high wave flooding [42,1,3,5]

District	Annual high wave flooding	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	Yes	6.4	14	0	0
	No	97.0	30	7	0
Oʻahu	Yes	12.7	35	5	0
	No	276.5	139	14	5
Maui	Yes	4.8	1	1	0
	No	170.9	78	9	1
	Undetermined	67.4	18	1	0
Hawaiʻi	Undetermined	335.4	82	36	0
All Districts	Yes	23.9	50	6	0
	No	544.4	247	30	6
	Undetermined	402.8	100	37	0

Table 4-3. Distribution of State roads, bridges, culverts, and tunnels exposed to coastal erosion [42,1,3,5]

District	Coastal erosion	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	Yes	4.4	5	1	0
	No	98.9	39	6	0
Oʻahu	Yes	10.2	14	1	0
	No	279.0	160	18	5
Maui	Yes	9.1	3	0	0
	No	166.6	76	10	1
	Undetermined	67.4	18	1	0
Hawaiʻi	Undetermined	335.4	82	36	0
All Districts	Yes	23.7	22	2	0
	No	544.5	275	34	6
	Undetermined	402.8	100	37	0

Table 4-4. Distribution of State roads, bridges, culverts, and tunnels exposed to all sea level rise hazards [42,1,3,5]

District	Sea level rise exposure area	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	Yes	8.6	25	1	0
	No	94.7	19	6	0
Oʻahu	Yes	21.0	66	6	0
	No	268.2	108	13	5
Maui	Yes	13.3	8	2	0
	No	229.9	89	9	1
Hawaiʻi	Yes	0.3	6	0	0
	No	335.2	76	36	0
All Districts	Yes	43.2	105	9	0
	No	928	292	64	6

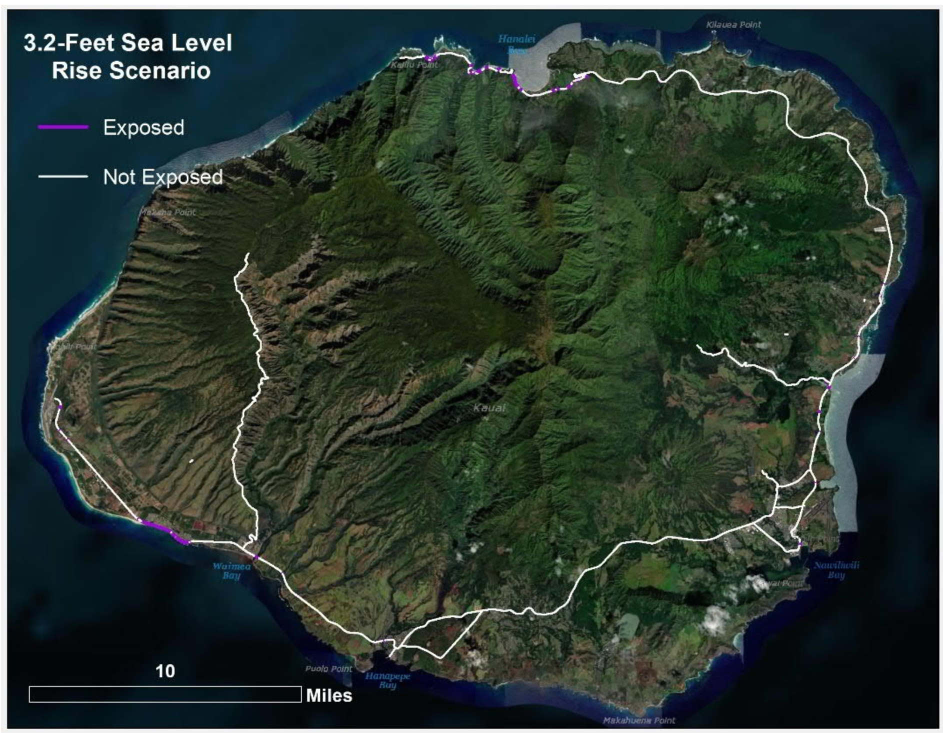

Figure 4-1. State road segments in the Kauaʻi District exposed to sea level rise hazards when considering a 3.2-feet sea level rise scenario [1,2]

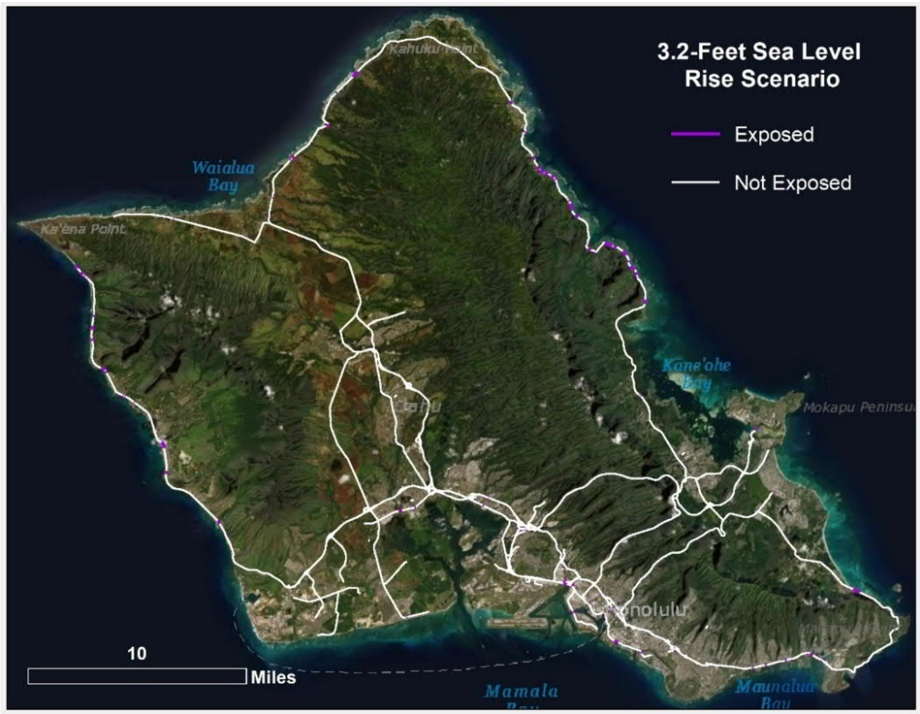

Figure 4-2. State road segments in the Oʻahu District exposed to sea level rise hazards when considering a 3.2-feet sea level rise scenario [1,2]

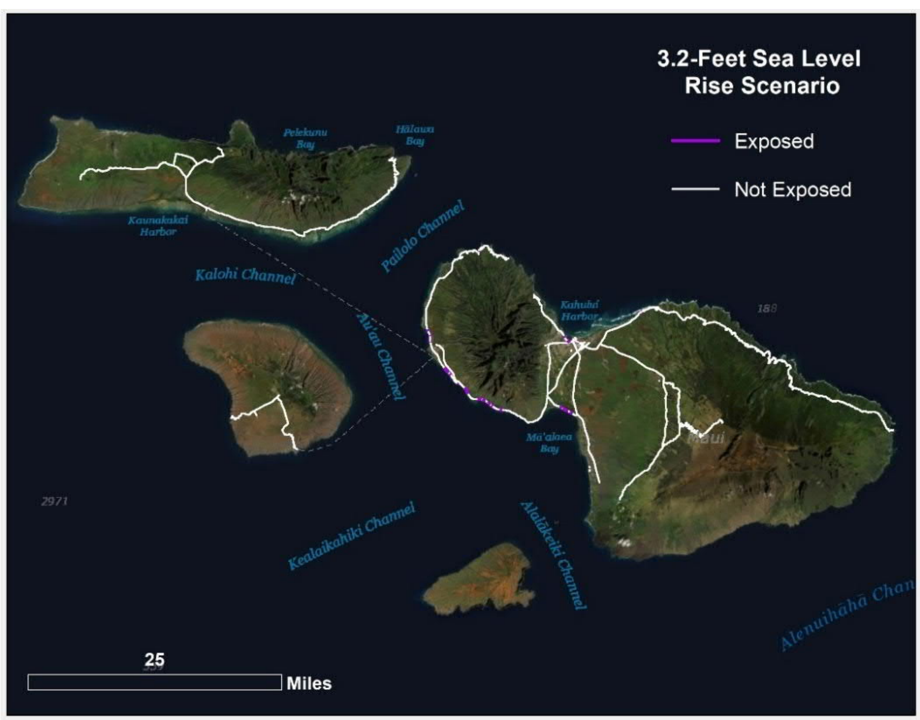

Figure 4-3. State road segments in the Maui District exposed to sea level rise hazards when considering a 3.2-feet sea level rise scenario [1,2]

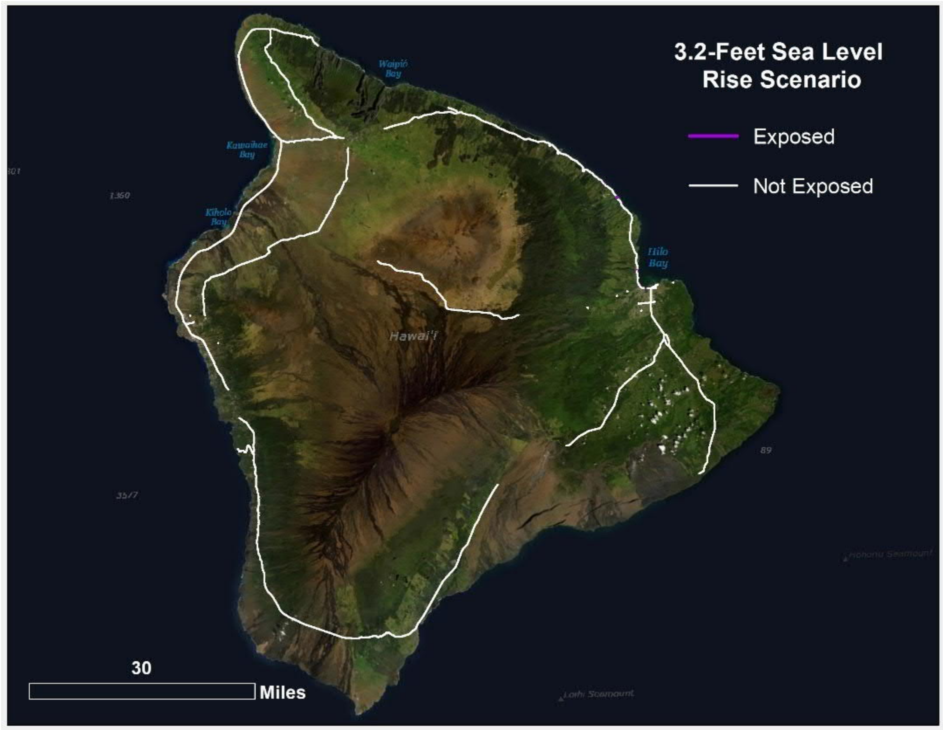

Figure 4-4. State road segments in the Hawai'i District exposed to sea level rise hazards when considering a 3.2-feet sea level rise scenario [1,2]

With respect to passive flooding:

- The exposure of road segments is relatively small across all Districts (1%).
- Culverts, and more importantly, bridges are considerably exposed (10% and 23%, respectively, and 21% of both assets when evaluated together).
- Actual exposure of all assets to groundwater inundation may be underestimated given that increased groundwater levels may pose problems to pavement sublayers and bridge foundations much before these levels can be observed on the surface.

The exposure of road segments to annual high wave flooding and coastal erosion is greater (4%) than their exposure to passive flooding (1%). Approximately 17% of assessed bridges and culverts are exposed to annual high wave flooding and 7% to coastal erosion. A large majority of the exposed assets across all sea level rise hazards are distributed throughout the O'ahu District.

4.4. RECOMMENDED ACTIONS FOR HIGHWAYS

- **Recommendation 4-1.** The protection of transportation assets exposed to sea level rise hazards may not be cost effective in the future. This means that exposed assets, and often adjacent assets, may need to be relocated or elevated. In extreme cases, where communities and their economic activities are relocated, roads may be decommissioned and new roads may be needed. Therefore, HDOT should engage closely with State and local agencies planning and managing the retreat process of communities (e.g., Office of Planning) to inform capital planning and maintenance teams.

- **Recommendation 4-2.** The increased presence of groundwater just below the surface also presents an increasing problem for existing assets in low-laying areas. Therefore, a more refined assessment to determine this impact is recommended to ensure that the reliability of transportation assets is not compromised. Such an assessment would include the generation of groundwater inundation data at various distances below surface levels critical to the structural performance of assets.
- **Recommendation 4-3.** Hazards such as coastal erosion are site-specific and, therefore, require field visits. Such visits would be important in the validation of areas identified in this current work as being exposed to coastal erosion. Some field work has already occurred as part of the work of Francis et al. [46]. In addition to gathering field condition data from HDOT's own highway maintenance team, HDOT should work collaboratively with State and county agencies familiar with local site conditions to share data on field conditions.

4.5. IMPROVEMENTS TO DATA AND MODELS TO ASSESS RESILIENCE OF SYSTEM

- **Recommendation 4-4.** HDOT can take a few steps now to understand better the exposure of the statewide asset inventory to sea level rise hazards while new research considers the integration of ice-sheet models to estimate the possible changes of ice sheet and their effects on sea levels. Some of these steps include (1) using sea level rise data generated in Francis et al. [46] in the development of groundwater inundation estimates, (2) updating annual high wave flooding and coastal erosion estimates for higher sea level rise scenarios consistent with this work, and (3) the generation of new annual high wave flooding and coastal erosion studies for the islands of Molokaʻi and Hawaiʻi.

CHAPTER 5. **STORM SURGE EXPOSURE ASSESSMENT**

5.1. PREVIOUS WORK AND EXISTING DATA

The Statewide Coastal Highway Program [46] used hurricane-related storm surge inundation estimates generated by the NOAA National Weather Service's (NWS) National Hurricane Center (NHC) [56,57] to determine the exposure of coastal highways to this hazard. The NHC generated these inundation depth values using the hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model [58]. This model has been used in past studies (e.g., [59,60]). Storm surge inundation depth values represent the ensemble of maximum inundation depth values at each individual grid cells generated by hypothetical hurricanes of a given category. The data for Hawai'i generated from this model considers hurricane events of Categories 1 through 4 and a high-tide scenario [61], but does not account for erosion, subsidence, or changes in sea level [57].

Hawai'i has only experienced one Category 4 hurricane in recorded history (Hurricane 'Iniki in 1992), making such events infrequent today. Given the importance of considering such unusual events due to their potential to cause significant damages and disruption, the State uses a hypothetical Category 4 hurricane in its catastrophic hurricane plan [62].

5.2. METHODOLOGY FOR EXPOSURE ASSESSMENT

Storm surge inundation depth values [56,57] are available as intervals of 1-foot increments above ground (e.g., 0 to 1 foot above ground, 1 to 2 feet above ground) until 16 feet of inundation depth above ground for each hurricane category. These values were used to identify the areas, and thus the assets in these areas, that may be inundated in the event of a hurricane. It was assumed that the elevation data used to determine inundated areas above ground and the elevation of road segments were comparable. This would facilitate the exposure assessment considering that only ranges of inundation depth values were provided. Bridges and culverts located in areas prone to experiencing storm surge were cataloged as exposed. Knowing that these assets have elevated elements, their exposure needs to be further evaluated on a site-by-site basis.

5.3. RESULTS OF EXPOSURE ASSESSMENT

The results by District and by hurricane category are presented in Table 5-1 and Figure 5-1 through Figure 5-4 (for illustration purposes, only road segments are shown in the figures). When examining the results obtained when considering hypothetical hurricanes of Category 4, for example, it is observed that nearly 8% of roads, 30% of bridges, and 12% of culverts are exposed to storm surge statewide. Assets in the O'ahu District are the most exposed. As previously indicated, determining the actual exposure of bridges and culverts requires additional evaluation and site visits. Figure 5-5 shows the distribution of bridges and culverts exposed to storm surge inundation by range of inundation depth values.

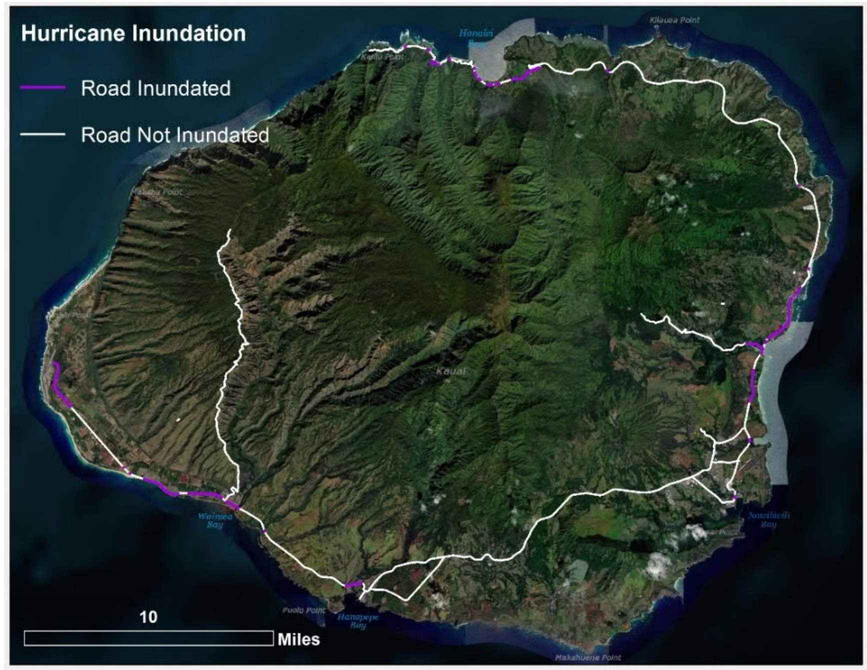

Figure 5-1. State road segments in the Kauaʻi District exposed to storm surge hazard [1,2]

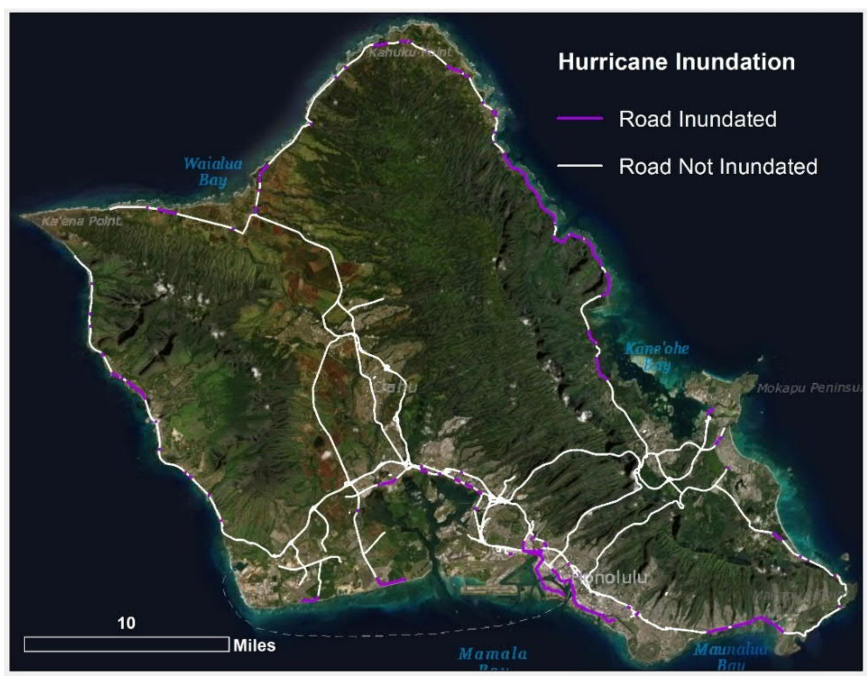

Figure 5-2. State road segments in the Oʻahu District exposed to storm surge hazard [1,2]

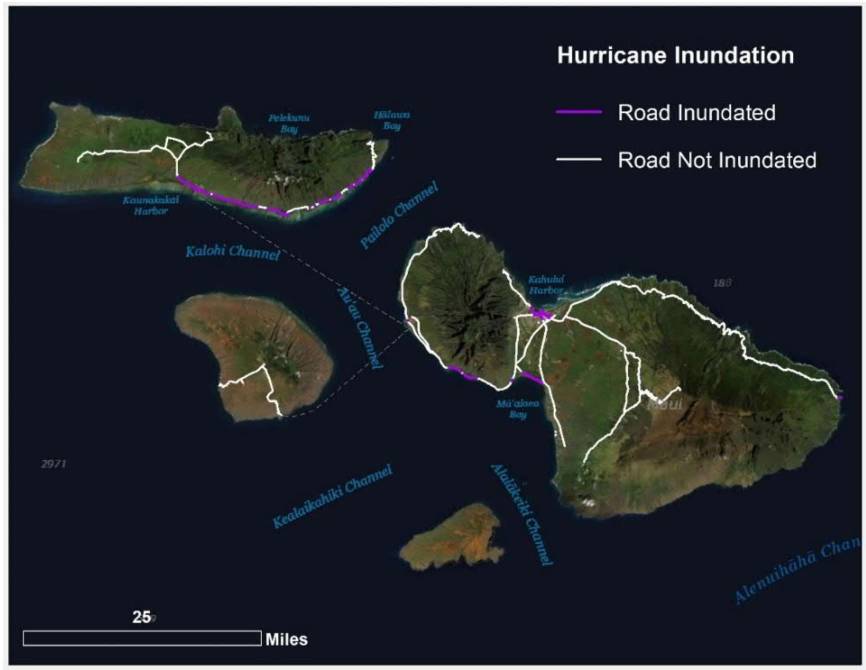

Figure 5-3. State road segments in the Maui District exposed to storm surge hazard [1,2]

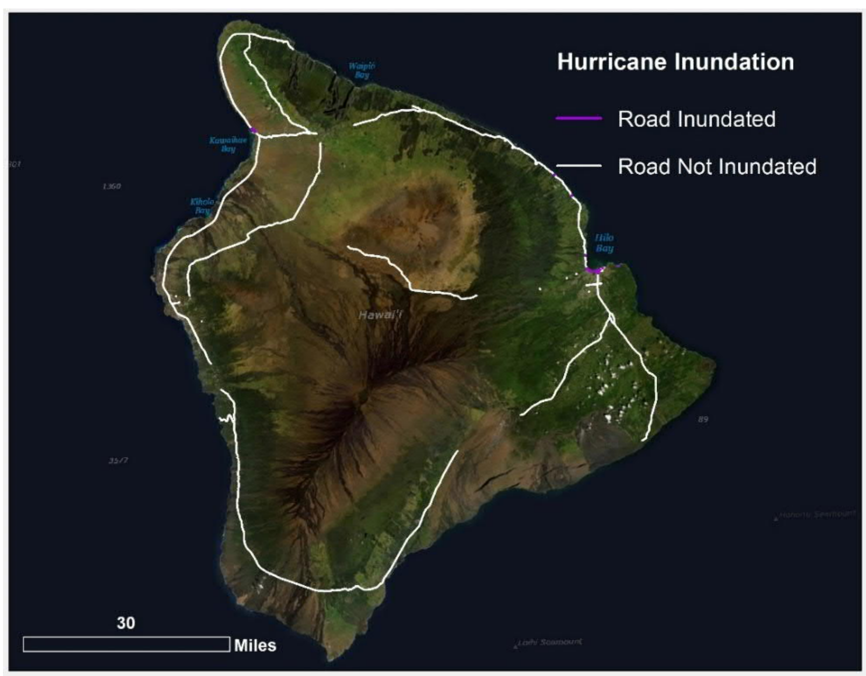

Figure 5-4. State roads in the Hawai'i District exposed to storm surge hazard [1,2]

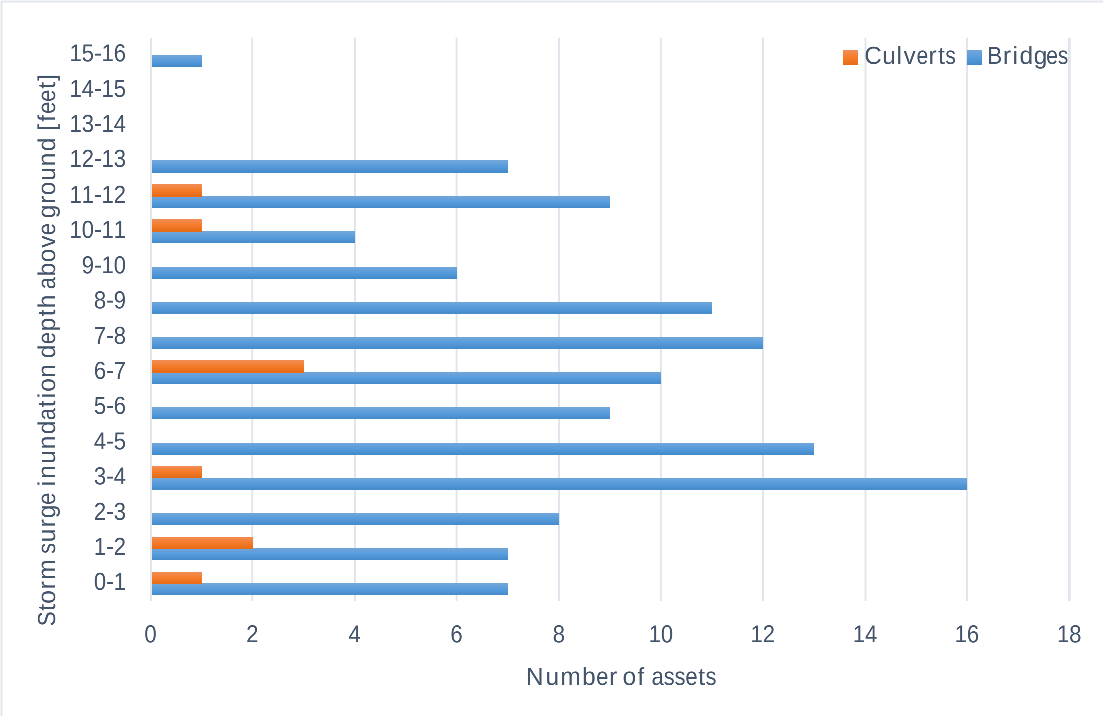

Figure 5-5. Distribution of bridges and culverts by storm surge inundation depth for hurricanes of Category 4

Table 5-1. Distribution of State roads, bridges, culverts, and tunnels exposed to storm surge by hurricane category [57,1,3,5]

District	Hurricane Category	Inundation Zone	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	1	Yes	3.2	18	0	0
		No	100.2	26	7	0
	2	Yes	5.0	19	0	0
		No	98.3	25	7	0
	3	Yes	10.0	20	1	0
		No	93.3	24	6	0
	4	Yes	13.3	23	2	0
		No	90.0	21	5	0

District	Hurricane Category	Inundation Zone	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
O‘ahu	1	Yes	13.2	41	3	0
		No	276.0	133	16	5
	2	Yes	22.9	56	3	0
		No	266.3	118	16	5
	3	Yes	29.2	69	4	0
		No	260.0	105	15	5
	4	Yes	36.6	78	5	0
		No	252.6	96	14	5
Maui	1	Yes	8.6	6	2	0
		No	234.5	91	9	1
	2	Yes	13.7	9	2	0
		No	229.5	88	9	1
	3	Yes	19.1	11	2	0
		No	224.0	86	9	1
	4	Yes	22.1	12	2	0
		No	221.0	85	9	1
Hawai‘i	1	Yes	0.1	5	0	0
		No	335.3	77	36	0
	2	Yes	0.2	5	0	0
		No	335.3	77	36	0
	3	Yes	0.6	6	0	0
		No	334.8	76	36	0
	4	Yes	2.0	7	0	0
		No	333.4	75	36	0
All Districts	1	Yes	25.1	70	5	0
		No	946	327	68	6
	2	Yes	41.8	89	5	0
		No	929.4	308	68	6
	3	Yes	58.9	106	7	0
		No	912.1	291	66	6
	4	Yes	74	120	9	0
		No	897	277	64	6

5.4. RECOMMENDED ACTIONS FOR HIGHWAYS

- **Recommendation 5-1.** Further evaluation of exposed bridges is required to identify bridges of concern given actual superstructure clearances and other site-specific factors affecting the vulnerability of bridges. This evaluation should include the consideration of hydrodynamic loads to determine the reliability of bridges and use the American Association of State Highway and Transportation Officials (AASHTO) guide specification for bridges vulnerable to coastal storms [63] and past work (e.g., [64]).
- **Recommendation 5-2.** There should be a coordinated effort between HDOT, the Hawaiʻi State Office of Planning (Coastal Zone Management Program), the Hawaiʻi Emergency Management Agency, and county emergency management offices to update existing evacuation and emergency response planning tools to consider information on additional routes anticipated to be impacted by storm surge. Evaluating the long-term viability of evacuation routes to emergency shelters should be especially considered given potential climate change impacts (refer to Section 5.5).
- **Recommendation 5-3.** In the anticipation of a hurricane, an Emergency Operations Center (EOC) may be activated. HDOT should consider further developing and implementing a process to enable direct communication with the EOC, the Hawaiʻi Emergency Management Agency, and county emergency management offices, the NOAA NWS Central Pacific Hurricane Center, and agencies that are involved in hurricane warning and science, and utility companies to exchange information on the anticipated impact of hurricane events to ensure resources are allocated for the prompt restoration of road services to support the delivery of emergency response services and the recovery of communities in the impacted areas. HDOT's hurricane response responsibility is to make sure the major Highway's (i.e., H-1, H-2 and H-3) are clear within 72 hours.

5.5. IMPROVEMENTS TO DATA AND MODELS TO ASSESS RESILIENCE OF SYSTEM

- **Recommendation 5-4.** While the frequency of hurricanes is expected to remain the same or increase in Hawaiʻi over time [65,66,67], scientists agree that hurricanes of high intensity (e.g., Category 4) may be observed with higher frequency [67]. Future collaboration with local researchers may need to focus on better understanding the implications of climate change on hurricane events affecting Hawaiʻi and the impacts of such events to the asset inventory. Some research has been completed in recent years (e.g., [68,69,52]) that may be relevant to future hazard studies.
- **Recommendation 5-5.** Probabilistic storm surge hazard maps for Hawaiʻi should be complementary products to the work described in Recommendation 5-4. Such maps, which would associate inundation depth values to different return periods, can be generated using the hypothetical hurricane events used in [56]. There is precedence of work performed in this area (e.g., [70]).

CHAPTER 6. **TSUNAMI EXPOSURE ASSESSMENT**

6.1. PREVIOUS WORK AND EXISTING DATA

Tsunamis are events triggered by geophysical events (e.g., earthquake events) that can result in coastal inundation. Information on selected coastal areas in Hawaiʻi that may be inundated by tsunami events can be accessed through the Statewide Coastal Highway Program [46]. Tsunami flow depth estimations used to determine the inundation states of these areas were obtained using the Non-hydrostatic Evolution of Ocean Wave (NEOWAVE) model [71,72] and simulated historical earthquake events (i.e., events that occurred in 1946, 1952, 1957, 1960, and 1964) and hypothetical earthquake events (i.e., two great Aleutian earthquakes with moment magnitudes of 9.3 and 9.6). The NEOWAVE model has been used in several studies (e.g., [73,74,75,76]). Tsunami flow depth estimations were originally computed by Professor Kwok Fai Cheung and team at the University of Hawaiʻi at Mānoa for county governments and the Hawaiʻi Emergency Management Agency. These estimations, based on historical and hypothetical events, have been used to generate tsunami evacuation zones [77] and to assess the exposure of communities [78], respectively.

6.2. METHODOLOGY FOR EXPOSURE ASSESSMENT

In [46], tsunami flow depth estimations were used to identify areas that could be inundated in the event of a tsunami, and such depths could, in theory, be associated with those inundated areas. However, the data provided in that exposure assessment (i.e., [46]) served only to distinguish inundated areas from non-inundated areas (i.e., no depth values were provided, and, therefore, such values could not be associated with an asset). Therefore, to facilitate this current exposure assessment, it was assumed that the elevation data used to determine inundated areas and the elevation of assets were comparable. If an area showed as inundated, then all assets contained in such an area were assumed to be inundated as well.

Furthermore, in [46], inundation levels generated by historical earthquake events were given larger weight than inundation levels generated by the hypothetical earthquake events. In this current work, both types of events are treated with the same level of concern because a comprehensive earthquake catalog (i.e., a wide collection of probable triggering events) is not available at this time, requiring the consideration of a wide range of possible events, whether historical or hypothetical. It is worth mentioning that tsunami events triggered by earthquake events along the Alaska-Aleutian Island arc, such as the hypothetical events, are of high concern due to (1) their short propagation time to Hawaiʻi (4.5–hour period), requiring that evacuations are completed in short timeframes [79], and (2) the implications of anticipated wave troughs with little attenuation [80].

6.3. RESULTS OF EXPOSURE ASSESSMENT

The results by District are presented in Table 6-1 and Figure 6-1 through Figure 6-4 (for illustration purposes, only road segments are shown in the figures). While roughly 18% of road segments statewide are exposed to tsunamis, the Districts with the largest relative exposure of road segments to tsunamis are Oʻahu (approximately 29%) and Kauaʻi (approximately 28%). A significant number of culverts and bridges are exposed to tsunami hazard: one-fifth of culverts statewide (nearly 21%), and one-third of bridges statewide (nearly 34%).

Table 6-1. Distribution of State roads, bridges, culverts, and tunnels exposed to tsunami hazard (historical or hypothetical) [46,1,3,5]

District	Tsunami Inundation Zone	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kaua'i	Yes	29.1	27	3	0
	No	74.3	17	4	0
O'ahu	Yes	84.6	77	9	0
	No	204.7	97	10	5
Maui	Yes	57.9	23	3	0
	No	185.2	74	8	1
Hawai'i	Yes	6.5	8	0	0
	No	328.9	74	36	0
All Districts	Yes	178.1	135	15	0
	No	793.1	262	58	6

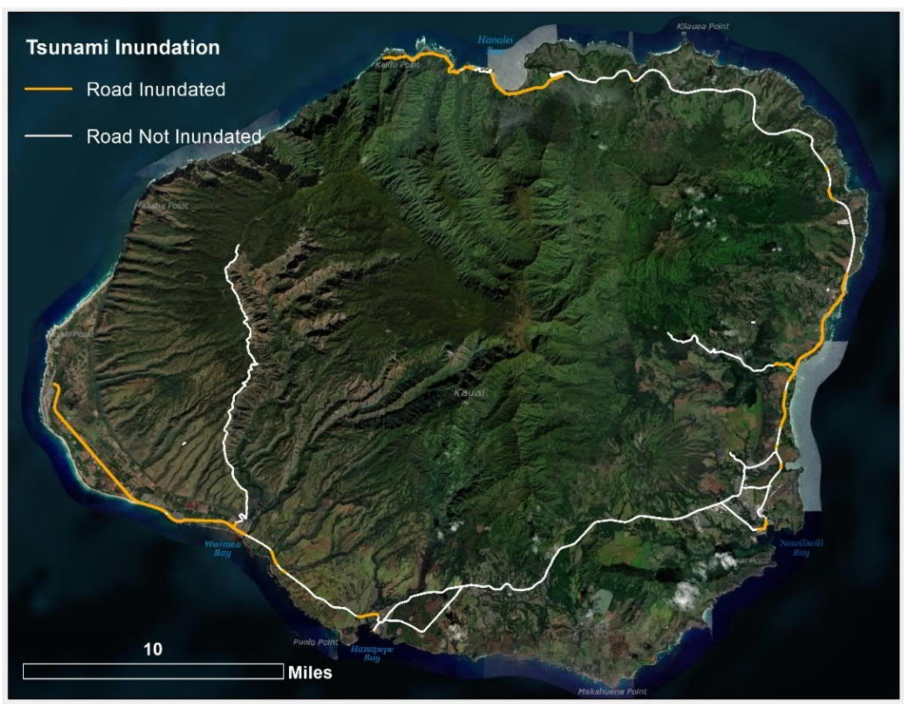

Figure 6-1. State road segments in the Kaua'i District exposed to tsunami hazard [1,2]

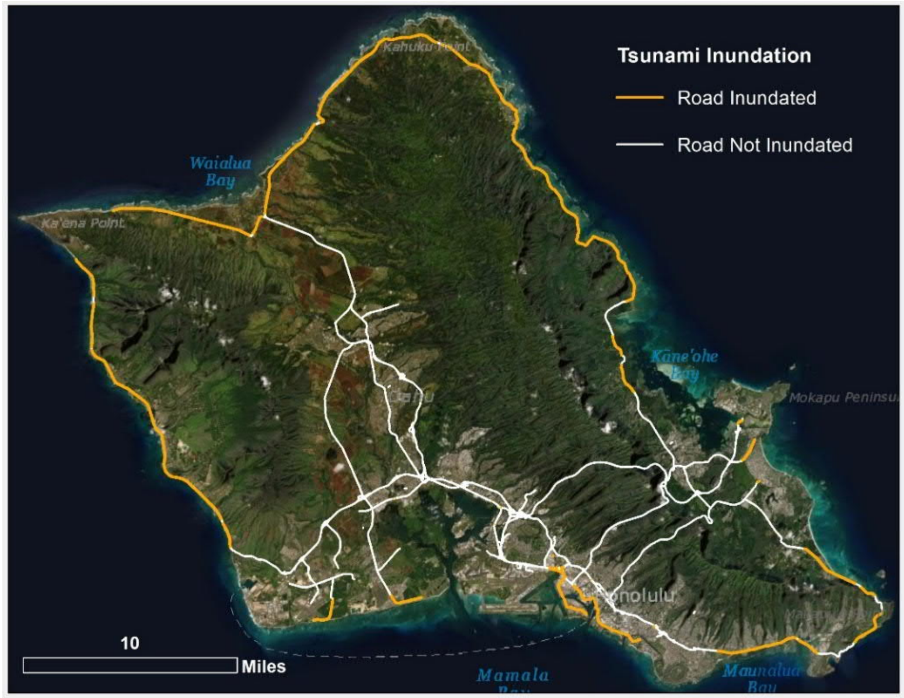

Figure 6-2. State road segments in the Oʻahu District exposed to tsunami hazard [1,2]

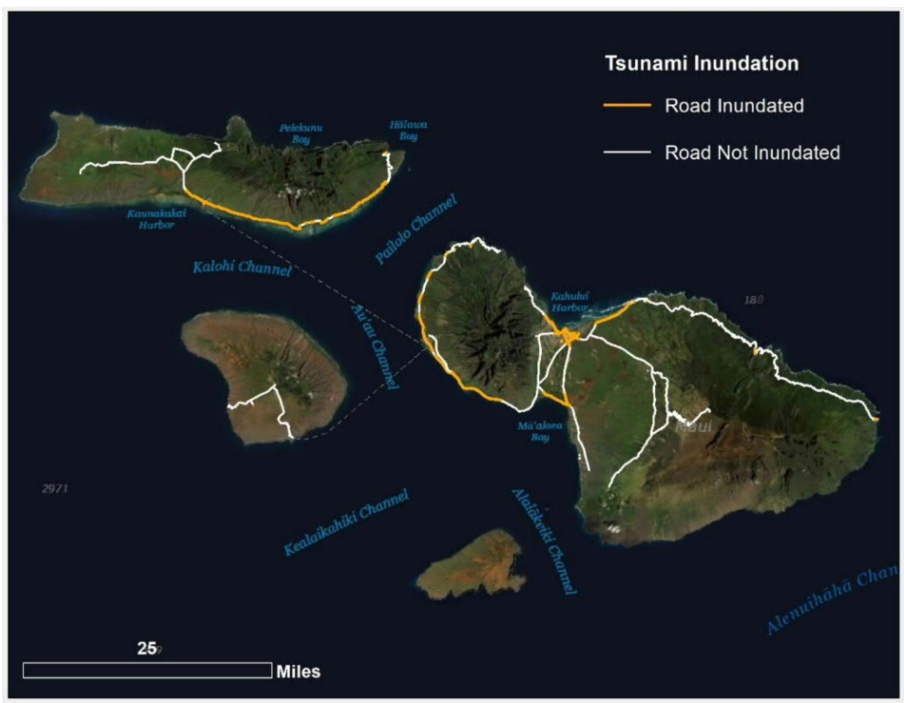

Figure 6-3. State road segments in the Maui District exposed to tsunami hazard [1,2]

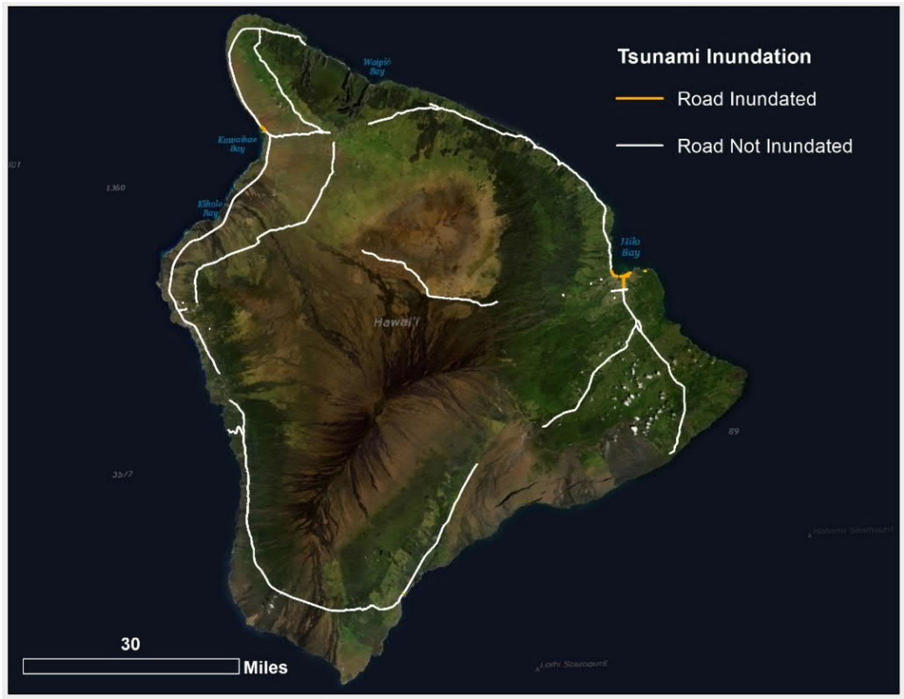

Figure 6-4. State road segments in the Hawai'i District exposed to tsunami hazard [1,2]

6.4. RECOMMENDED ACTIONS FOR HIGHWAYS

- **Recommendation 6-1.** Given the significant number of bridges that are exposed to tsunami events, HDOT should create a bridge evaluation program/study focused on determining the reliability of bridge structures to anticipated tsunami loads. This program should rely on the upcoming AASHTO guide specification for tsunami design of highway bridges [81], the inventory of exposed bridges identified in this study, models available at the University of Hawai'i at Mānoa (e.g., NEOWAVE), and similar past work (e.g., [82]). The tsunami hazard data to be provided with the new AASHTO guide specification (i.e., flow depth and velocity) correspond to an annual exceedance probability of 0.1%, which is consistent with the seismic hazard used for bridge design. These data were generated by considering all identified seismic source zones around the Pacific Ocean.
- **Recommendation 6-2.** There should be a coordinated effort between HDOT, the Hawai'i State Office of Planning (Coastal Zone Management Program), the Hawai'i Emergency Management Agency and county emergency management offices to update existing evacuation and emergency response planning tools to consider information on additional routes anticipated to be impacted by tsunami events.
- **Recommendation 6-3.** At the onset of a tsunami triggering event, an EOC may be activated. HDOT should consider developing and implementing a process to enable direct communication with the EOC, the NOAA Pacific Tsunami Warning Center, the USGS Hawaiian Volcano Observatory (HVO), and other agencies that are involved in tsunami warning and science (refer to [83] for additional context). The purpose would be to exchange information on the anticipated impact of such a tsunami event to ensure resources are allocated

for the prompt restoration of road services to support the delivery of emergency response services and the recovery of communities in the impacted areas.

6.5. IMPROVEMENTS TO DATA AND MODELS TO ASSESS RESILIENCE OF SYSTEM

» **Recommendation 6-4.** Future collaboration with the University of Hawai‘i at Mānoa may need to focus on better understanding the implications of climate change, specifically sea level rise, on tsunami events affecting Hawai‘i. Some research has been completed in recent years (e.g., [84,85,86]) that may be relevant to future studies.

» **Recommendation 6-5.** An additional area of collaboration with the University of Hawai‘i at Mānoa and the team authoring the AASHTO guide specification for tsunami design of highway bridges may be the expansion of the earthquake catalog containing the tsunami triggering events. This expansion would focus on including stochastic events of various return periods that could be used to generate probabilistic tsunami hazard maps for Hawai‘i. These scenarios, which may include local earthquake events [87], would be used in future risk assessments. Events recorded in the catalog could also be used to support the development of scenario-based emergency response simulations and planning.

CHAPTER 7. **WILDFIRE EXPOSURE ASSESSMENT**

7.1. PREVIOUS WORK AND EXISTING DATA

Hawai'i is at greatest exposure to wildfires from April to October, which corresponds to the typical dry months [50]. Wildfires are more likely to occur on the drier leeward side of the islands but can occur on the windward side as well [50,88]. The number of wildfires per year has increased four-fold in recent decades, in part due to the increase of rain shadows, episodic drought, human-caused ignition, and invasive species including nonnative grass and shrubs, which provide ample fuel for fires [89]. Grasslands and shrublands have become the predominant vegetation, covering about 24% of the State's total land [90]. El Nino also plays a role as it initially brings wetter summers supporting increased grassland growth, which serves as fuel to the fires, then turns to drought and high-risk fire conditions [50,89]. Nonnative derived savannas are responsible for 80% of the area burned annually [89]. Almost all fires, more than 99%, are ignited by human activity (e.g., through human error or arson), while volcanic activity and lightning play a very minor role [88,90]. In fact, vegetated areas along roads where there are higher population densities account for much of the wildfire ignition [88].

There is a general concern that wildfire risk will increase over the coming decades. In part, this is linked to a continued increase of grasslands and shrublands, population growth, increase in drying in arid lowland areas, and increase in year-to-year variability in rainfall that includes increased drought conditions [89]. Over time, the arid lowland areas may become so dry that this situation would lead to a reduction in flammability as vegetation growth reduces thereby reducing fire fuel. Having said this, fire probability is anticipated to increase by as much as 375% by late century under a high greenhouse gas emissions scenario [89].

Two primary sources of spatial wildfire data are produced for Hawai'i. One source, the Communities at Risk from Wildfires [91], provides geospatial data with communities rated in terms of wildfire risk. The rating is based on 36 hazard components such as community engagement, narrow streets, fire planning and preparedness, and vegetation near houses. Environmental hazards include rainfall averages, past exposure to drought/severe weather, and ignition risk. Another source [88,92] uses past wildfire ignitions from 2000 to 2012 to estimate the number of ignitions per square mile per year (wildfire ignition density). Neither data source is a predictor of future wildfire probability, but presents wildfire hazard based on today's societal and environmental conditions that may lead to wildfire events in the future.

7.2. METHODOLOGY FOR EXPOSURE ASSESSMENT

For this analysis, wildfire ignition density estimates [88,92] were used to determine the exposure of the roadway assets to wildfire. The level of resolution of these maps was 1 mile (1-mile grids spatially distributed throughout the State). This current exposure assessment assigned the ignition density to the assets located in the 1-mile grid. This assessment could not determine:

- The actual proximity of wildfire ignitions to an asset (i.e., a wildfire ignition located in a neighboring grid could be closer to an asset than an ignition in the grid where the asset is located)
- Whether such events could affect the State road network due to site-specific conditions at the location of the asset
- The triggering factor of ignitions (e.g., changing vegetation)

7.3. RESULTS OF EXPOSURE ASSESSMENT

The results by District are summarized in Table 7-1 and presented in Figure 7-1 through Figure 7-4 (for illustration purposes, only road segments are shown in the figures). The wildfire ignition density maps [92] covered areas where approximately 98% of the State road network is located. This means that the exposure of 2% of the State road network, including 1% of bridges and 3% of culverts, could not be determined (assets identified as "undetermined" in Table 7-1). Nearly 10% of the State road network, including 10% of bridges and 3% of culverts, is in areas that have not been exposed to wildfires (assets identified as "not exposed" in Table 7-1). The remainder of the State road network is in areas that have been exposed to wildfires. Most of these exposed assets are in the Oʻahu District. Roughly 14% of the State road network, including 24% of bridges and 25% of culverts, is in areas that have been exposed to more than one wildfire per year. The remaining assets (i.e., 74% of the State road network, including 65% of bridges, 70% of culverts, and all tunnels) are in areas that have been exposed to one wildfire per year or less (a fraction of an event can be obtained due to the yearly scale of the data and the spatial smoothing technique applied in the model to estimate wildfire ignition density; refer to [88,92]).

Table 7-1. Distribution of State roads, bridges, culverts, and tunnels exposed to wildfires (based on past wildfire ignitions from 2000 to 2012) [92,1,3,5]

District	Wildfire ignition density (events per square mile per year)	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
Kauaʻi	More than 1	10.9	5	0	0
	1 or less	91.2	39	6	0
	Not exposed	0	0	0	0
	Undetermined	1.2	0	1	0
Oʻahu	More than 1	106.5	86	11	0
	1 or less	172.5	85	7	5
	Not exposed	0	0	0	0
	Undetermined	10.3	3	1	0
Maui	More than 1	19.1	6	3	0
	1 or less	192	64	8	1
	Not exposed	26.5	26	0	0
	Undetermined	5.6	1	0	0
Hawaiʻi	More than 1	2.7	0	4	0
	1 or less	266.4	69	30	0
	Not exposed	65.8	13	2	0
	Undetermined	0.6	0	0	0
All Districts	More than 1	139.2	97	18	0
	1 or less	722.1	257	51	6
	Not exposed	92.3	39	2	0
	Undetermined	17.7	4	2	0

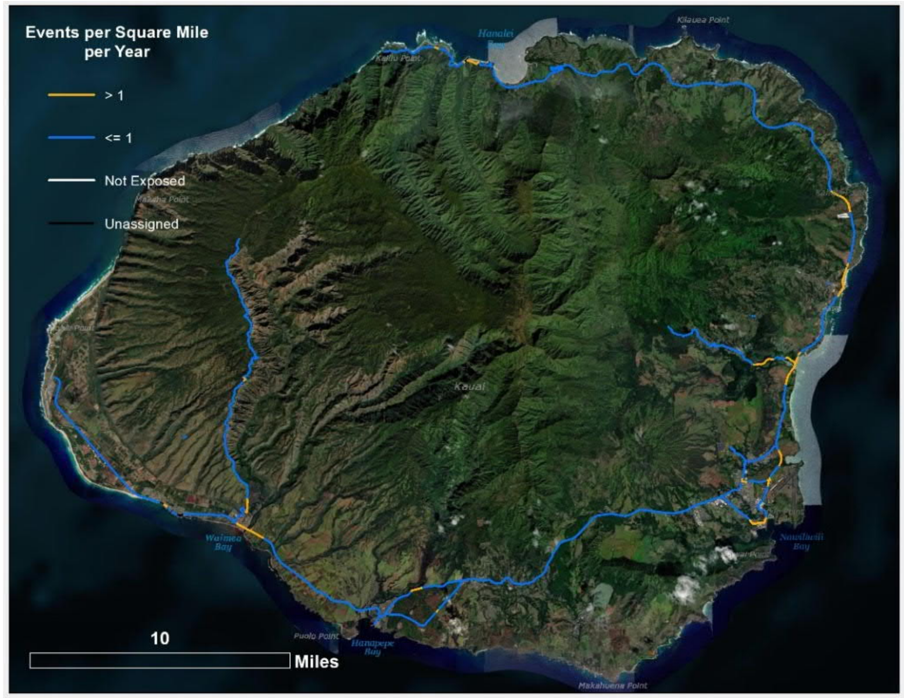

Figure 7-1. State road segments in the Kaua'i District exposed to wildfire hazard using wildfire ignition events per square mile per year (based on past wildfire ignitions from 2000 to 2012) [1,2]

Figure 7-2. State road segments in the O'ahu District exposed to wildfire hazard using wildfire ignition events per square mile per year (based on past wildfire ignitions from 2000 to 2012) [1,2]

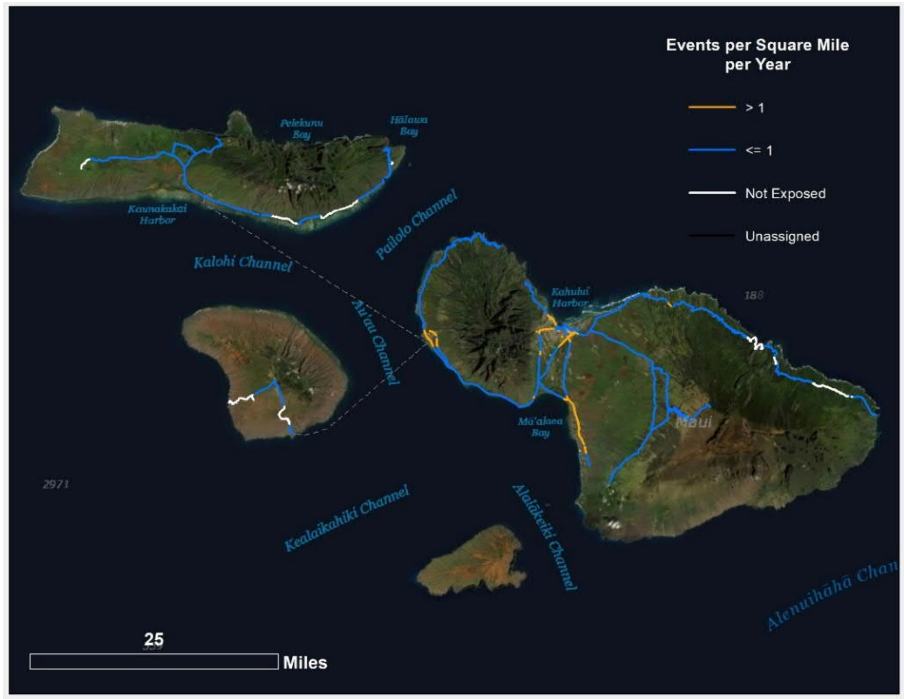

Figure 7-3. State road segments in the Maui District exposed to wildfire hazard using wildfire ignition events per square mile per year (based on past wildfire ignitions from 2000 to 2012) [1,2]

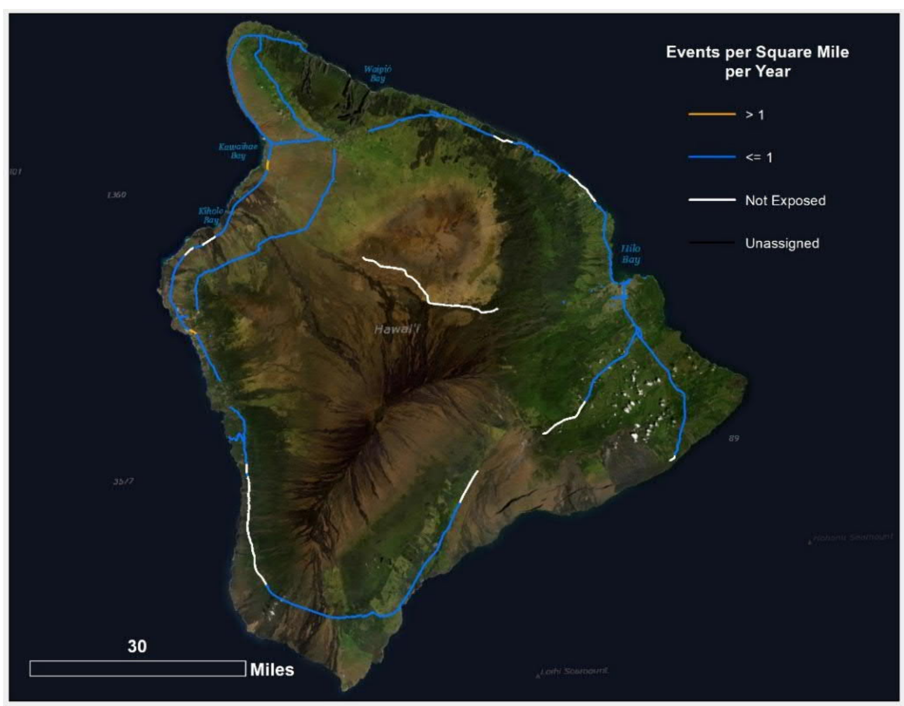

Figure 7-4. State road segments in the Hawaiʻi District exposed to wildfire hazard using wildfire ignition events per square mile per year (based on past wildfire ignitions from 2000 to 2012) [1,2]

7.4. RECOMMENDED ACTIONS FOR HIGHWAYS

- **Recommendation 7-1.** On-site evaluations are required to determine the exposure of roads to wildfires (i.e., the conditions that could increase the likelihood of a wildfire). Certain locations will require routinely clearing debris and vegetation along roads to reduce wildfire fuel sources. Other locations may need shoulder areas or larger shoulder areas than what currently exists to increase the distance between road users and roadside vegetation. In selected circumstances, such features could enable emergency response personnel to travel along critical routes during wildfires.
- **Recommendation 7-2.** HDOT should partner with the Hawai‘i Wildfire Management Organization and local authorities, including fire departments, to support wildfire education that specifically covers risks along roadways.
- **Recommendation 7-3.** Advancements in wildfire predictive technologies and real-time monitoring can support wildfire evacuation and emergency response efforts. HDOT should partner with State and local organizations to secure and improve such capabilities to identify critical parts of the road network to support such operations.

7.5. IMPROVEMENTS TO DATA AND MODELS TO ASSESS RESILIENCE OF SYSTEM

- **Recommendation 7-4.** Improvements in climate data projections would greatly enhance the opportunity to characterize the wildfire hazard in Hawai‘i for the next few decades, especially on the leeward side where climate is anticipated to be drier and temperatures are expected to increase. HDOT should monitor new research taking place at the University of Hawai‘i at Mānoa that examines such future conditions.
- **Recommendation 7-5.** HDOT should determine the effects of past wildfires on the State network, especially in parts of the network with asphalt material, identifying common and recurring impacts as well as repair and reconstruction interventions, to understand better wildfire events on the network and anticipate probable future consequences, including repair cost estimates. Asphalt material is sensitive to temperatures and can be damaged in a wildfire. Moreover, due to the composition of this material, in very intense temperatures, asphalt can ignite and allow wildfires to spread along and across roads.

CHAPTER 8. **LAVA FLOW EXPOSURE ASSESSMENT**

8.1. PREVIOUS WORK AND EXISTING DATA

Hawai‘i has six active volcanoes, four of which are in the Hawai‘i District—Kīlauea, Mauna Loa, Hualālai, and Mauna Kea. Two other active volcanoes are Haleakalā in the Maui District and Lō‘ihi, a submarine volcano south of the Island of Hawai‘i. In particular, Kīlauea and Mauna Loa pose a very high threat to the Hawai‘i District and Hualālai a high threat to the Maui District [93]. The potential damages and disruption caused by volcano-related hazards, especially lava flow hazard, have focused research in applied volcanology on reducing these probable consequences [94]. Lava flows typically erupt from a volcano's summit or along rift zones on its flanks, and travel downslope toward the ocean. Such flows can be dated and mapped [83], including using airborne radar [95]. This information is critical to determining the frequency of past lava inundation and the characterization of lava flow hazard.

The lava flow hazard map for the Hawai‘i District [96] is divided into 9 zones, with lava flows most likely to occur in Zone 1 and least likely in Zone 9 (brief descriptions are provided in Table 8-1; refer to [96] for additional information). The hazard zones consider the larger topographic features of the volcanoes that will affect the distribution of lava flows. The lava flow hazards map for the Maui District [97] is divided into 4 zones (brief descriptions are provided in Table 8-2; refer to [97] for additional information). See Table 8-3 for an interpretation of the suggested relationship between these zones and those of the map for the Hawai‘i District.

Table 8-1. Descriptions of lava flow hazard map zones in the Hawai‘i District [96]

Zone	Description
1	Includes summits and rift zones of Kīlauea and Mauna Loa, where vents have been repeatedly active in historical time.
2	Areas adjacent to and downslope of Zone 1. 15% to 25% of Zone 2 has been covered by lava since 1800, and 25% to 75% has been covered within the past 750 years. Relative hazard within Zone 2 decreases gradually as one moves away from Zone 1.
3	Areas less hazardous than Zone 2 because of greater distance from recently active vents and (or) because of topography. 1% to 5% of Zone 3 has been covered since 1800, and 15% to 75% has been covered within the past 750 years.
4	Includes all of Hualālai, where the frequency of eruptions is lower than that for Kīlauea or Mauna Loa. Lava coverage is proportionally smaller, about 5% since 1800, and less than 15% within the past 750 years.
5	Area on Kīlauea currently protected by topography.
6	Two areas on Mauna Loa, both protected by topography.
7	Younger part of dormant volcano Mauna Kea. 20% of this area was covered by lava in the past 10,000 years.
8	Remaining part of Mauna Kea. Only a small percent of this area has been covered by lava in the past 10,000 years.
9	Kohala Volcano, which last erupted over 60,000 years ago.

Table 8-2. Descriptions of lava flow hazard map zones in the Maui District [97]

Zone	Description
1	Rift Zone - likely site of eruption
2	Downslope area that lies within the lava sheds of rift zone vents
3	Area where lava is unlikely to encroach owing to topographic obstructions
4	Shielded from lava flows in excess of 100,000 years

Table 8-3. Proposed equivalence of lava flow hazard map zones [97,98]

Hawai'i District	Maui District
Zone 3	Zone 1
Zone 4	Zone 2
Zone 6	Zone 3

8.2. METHODOLOGY FOR EXPOSURE ASSESSMENT

The lava flow hazard maps for the Hawai'i District [96] and the Maui District [97] were used to determine the exposure of the road network asset inventory. Zone 1 in the Hawai'i District approximates the shape and extent of known rift zones, and consequently, is the area of highest concern. Zones 2 and 3 in the Hawai'i District and Zone 1 in the Maui District are the next areas of most concern. Assets that are in these four zones are the most exposed to lava flow hazard.

8.3. RESULTS OF EXPOSURE ASSESSMENT

The results are presented in Table 8-4 and Table 8-5 and Figure 8-1 and Figure 8-2. In the Hawai'i District, 43.6% of the road network, including 17.1% of bridges and 41.7% culverts, is in Zones 1 through 3. In the Maui District, 2.3% of the road network, including 4.1% of bridges, is in Zone 1.

Table 8-4. Distribution of State roads, bridges, culverts, and tunnels exposed to lava flow hazard in the Hawai‘i District [1,3,5]

Zone	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
1	3.1	0	0	0
2	51.9	0	0	0
3	91.1	14	15	0
4	45.7	0	11	0
5	0	0	0	0
6	8.0	1	1	0
7	0	0	0	0
8	90.1	58	4	0
9	45.6	9	5	0
Total	335.4	82	36	0

Table 8-5. Distribution of roads, bridges, culverts, and tunnels exposed to lava flow hazard in the Maui District [1,3,5]

Zone	Road (miles)	Bridges (units)	Culverts (units)	Tunnels (units)
1	5.7	4	0	0
2	16.6	14	0	0
3	1.1	1	0	0
4	219.7	78	11	1
Total	243.1	97	11	1

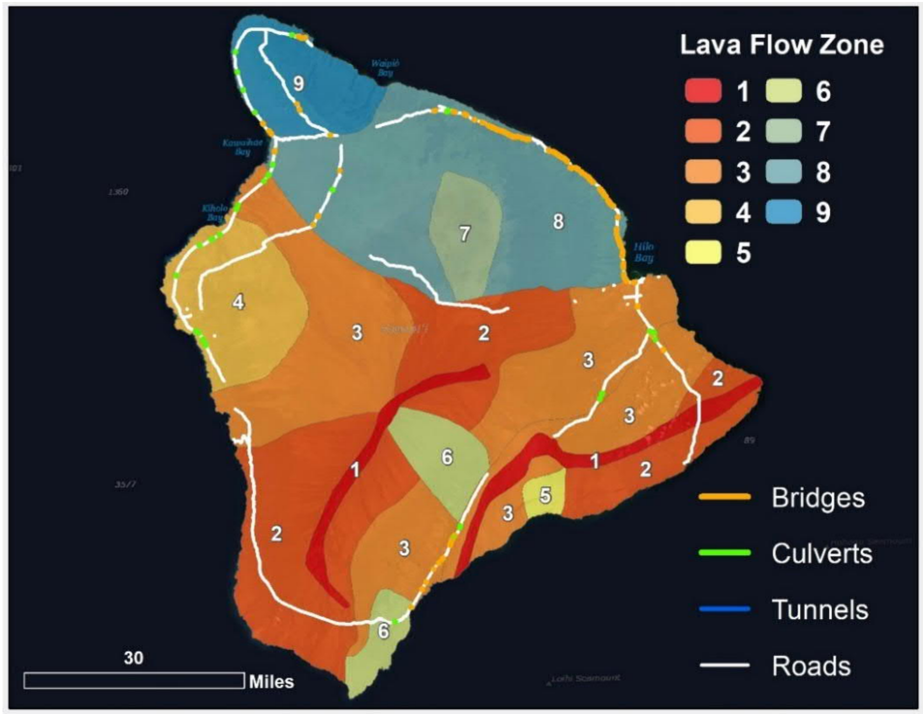

Figure 8-1. State roads, bridges, culverts, and tunnels in the Hawai'i District exposed to lava flow hazard [96,1,3,5,2]

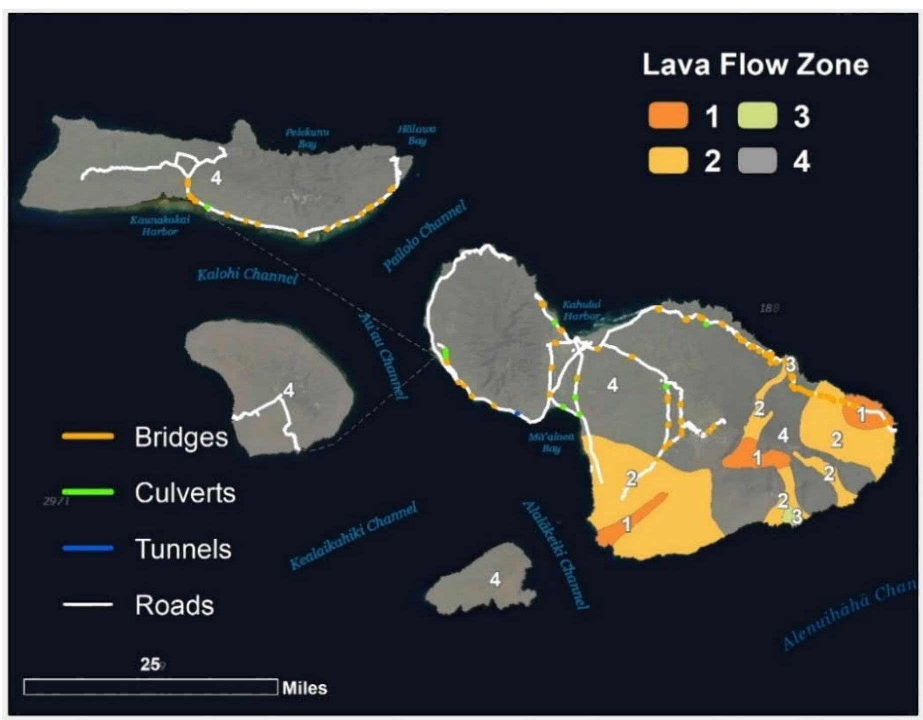

Figure 8-2. State roads, bridges, culverts, and tunnels in the Maui District exposed to lava flow hazard [97,1,3,5,2]

It is worth noting that hazard zones have approximate boundaries and represent the hazard in relative terms (i.e., one zone compared to another). Therefore, these zones can only be used for general planning purposes [96].

8.4. RECOMMENDED ACTIONS FOR HIGHWAYS

- **Recommendation 8-1.** When evaluating existing prioritized assets (i.e., those in Zones 1 through 3 in the Hawaiʻi District and in Zone 1 in the Maui District), HDOT should evaluate the level of network redundancy to allow alternative access to areas served by the network, and improve redundancy if this level is found to be inadequate. Lava flow diversion strategies may be additionally considered. The assessment of network redundancy and lava flow diversion strategies should also be considered when conducting major improvements to existing State highways or constructing new assets in the areas most exposed to lava flow hazards.
- **Recommendation 8-2.** When an eruption occurs, the USGS HVO estimates the probable paths of lava flow using DEMs representing the topographies of volcanoes, enabling them to identify the steepest descent paths, and broad inundation zones defined by historical lava flow path data. The HVO also estimates lava flow travel times based on the advance rates of active flows and those of earlier flows in the same area [99]. During eruptions that require the activation of an EOC, the information generated by the HVO can be accessed by State agencies through the activated EOC. HDOT should consider developing and implementing a process to enable direct communication with the EOC and the HVO to identify assets along the State road network that may be affected by lava flows. This development should review communication during past emergencies, including the eruption of Kīlauea in 2018.

8.5. IMPROVEMENTS TO DATA AND MODELS TO ASSESS RESILIENCE OF SYSTEM

- **Recommendation 8-3.** HDOT should assess the effects of previous lava flows on the highway network, identifying common and recurring impacts, leading to improving the estimation of probable future consequences.
- **Recommendation 8-4.** This assessment should also consider seismic hazard events that have occurred in combination with past lava flow events. These combined events can result in significant damage to roadway assets.
- **Recommendation 8-5.** Underground voids created by lava tubes are hazards associated with active and inactive volcanic zones and lava flows. During the lava flow event of 2018, field crews used ground-penetrating radar to identify the locations of large voids that posed a potential hazard on State highways. These potential hazards were successfully identified in the Puna District of the Big Island, and HDOT subsequently undertook appropriate countermeasures, such as road closures, to protect the traveling public. There is a need to continue collecting field data to identify voids in other locations. This information can be used to complement the results of this exposure assessment and future risk analyses.
- **Recommendation 8-6.** HDOT should also assess other types of volcano-related hazards, including pyroclastic flows, air-fall tephra, and volcanic gases, along with their potential impacts on highways.

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