HONOAPI'ILANI HIGHWAY IMPROVEMENTS PROJECT,
WEST MAUI: UKUMEHAME TO LAUNIUPOKO

Appendix 3.13 – Climate Change and Sea Level Rise - Supplemental Information

November 2025

Prepared for

Honoapi'ilani Highway Improvements

Prepared by

wsp

November 2025

Contents

Sea Engineering, Inc
Sea Level Rise Wave Inundation Study

November 2025

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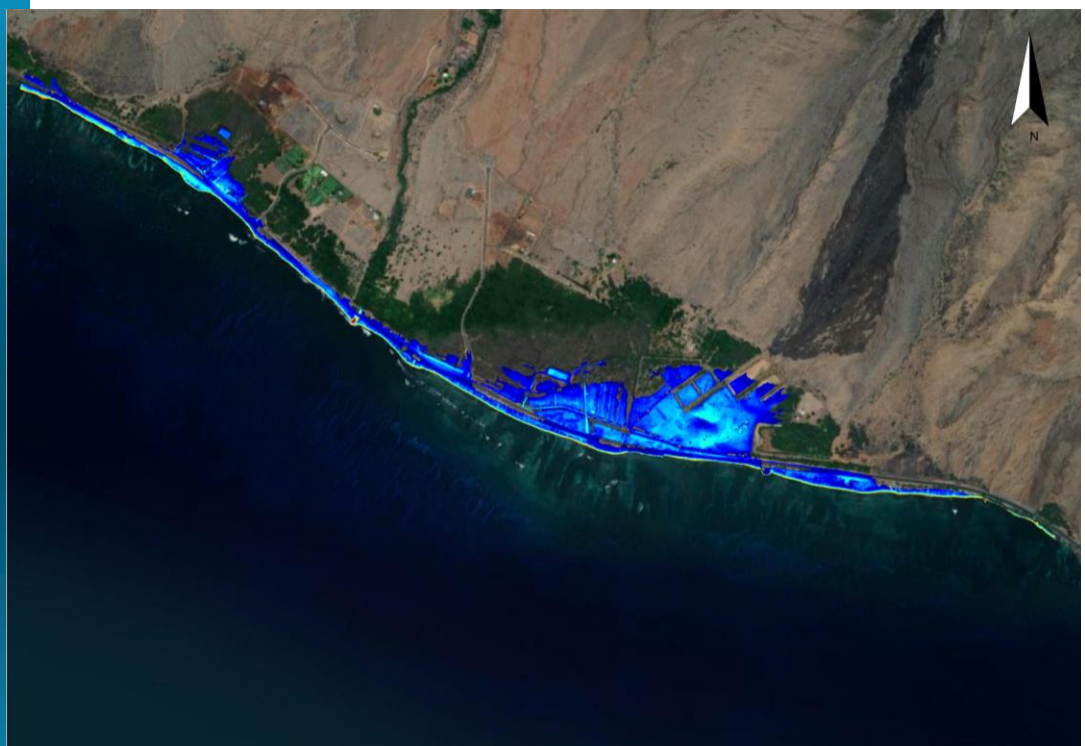
Honoapiilani Highway Realignment

Honoapiilani Highway
Olowalu and Ukumehame, Maui, Hawaii

February 2024



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EXECUTIVE SUMMARY

Sea Engineering, Inc. (SEI) has been contracted by WSP to conduct a sea level rise (slr) and wave inundation study for proposed roadway alignment alternatives along Honoapiilani Highway at Ukumehame and Olowalu, Maui. Four (4) alternative highway realignments are being proposed. Due to the low-lying nature of this portion of coastline, the alignment alternatives may be susceptible to future wave flooding with slr. Project tasks included a comprehensive summary of the current slr projections, review of existing Hawaii sea level rise data tools such as SLR-XA, site-specific numerical modeling of wave induced flooding for a future sea level of 0.98 m (3.2 ft) for existing topography and each of the four (4) highway realignment alternatives, summary of project area FEMA flood hazard zones, and general summary of coastal highway adaptation strategies. Key findings are summarized below.

Sea Level Rise Projections

Sea level rise projections are provided by the Intergovernmental Panel on Climate Change (IPCC) and the *Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force* ("Task Force"). Key guidance from the most recent IPCC AR6 and Task Force reports specific to Maui are the following:

- According to the new IPCC AR6 report, the most aggressive, plausible sea level rise scenario is the SSP5-8.5. On Maui, SSP5-8.5 projects that the sea level will rise 0.30 m (1.0 ft) by 2050, 0.50 m (1.7 ft) by 2070, and 0.96 m (3.2 ft) by 2100.
- The Task Force's *Intermediate* scenario projects sea level on Maui will rise 0.32 m (1.1 ft) by 2050, 0.57 m (1.9 ft) by 2070, and 1.21 m (4.0 ft) by 2100.
- The *Intermediate-High* scenario projects 0.40 m (1.3 ft) by 2050, 0.86 m (2.8 ft) by 2070, and 1.83 m (6.0 ft) by 2100.

In Hawaii, there is accepted guidance to use 0.98 m (3.2 ft) of slr as a planning target for 2100 with discussion of 1.83 m (6.0 ft) as an additional target in that time frame. The fifth IPCC report, AR5, was utilized when developing these guidelines. The most aggressive slr curve, resulting from the highest warming scenario (RCP8.5), was used to project this slr elevation (0.98 m [3.2 ft]) by the year 2100. The discussion for 1.83 m (6.0 ft) as an additional safety factor was developed around the 2017 Task Force *Intermediate-High* regional projection for Hawaii, which projected approximately 1.83 m (6.0 ft) of slr by 2100. This was revised in an important conclusion of the 2022 Task Force report. The 2022 report indicates that the Task Force's revised *Intermediate* rate is recommended for planning and design purposes in Hawaii. As outlined above, this projects 1.21 m (4.0 ft) by 2100.

SEI Numerical Modeling of Sea Level Vulnerability

The XBeach non-hydrostatic (XBeach-NH) numerical model was used to simulate nearshore wave propagation and wave-driven overland flooding of the study area. The model is two-dimensional and high resolution, and has been verified to produce accurate representations of wave heights and wave patterns across complex bathymetry, and is able to simulate wave-driven overland flooding for an input wave, sea level, and wind scenario. Model output includes flooding extent and corresponding maximum flood depths and elevations over the study area to assist in planning and design of proposed roadway alignments.

Three (3) individual XBeach-NH model grids were developed to encompass the study areas and proposed roadway alignments along the shoreline. Each model has a spatial resolution of 2 m (6.6 ft). Five (5) model topographies were input into the model to represent existing conditions and alternative highway alignments 1 through 4. Inputs to the model included the same annually recuring wave parameters that have been used in SLR-XA, the mean higher high water (mhhw) level of 0.35 m (1.1 ft) and slr of 0.98 m (3.2 ft) above mean sea level (msl), for a total still water input of 1.33 m (4.3 ft) above msl.

Based on the model results for the Olowalu region, highway alignment alternatives 3 and 4 are the least susceptible to potential flooding for the annual wave event where neither of these highway alignments are impacted by the modeled flooding. Highway alignment alternative 1 was found to be the most susceptible to potential flooding in the Olowalu region for an annual wave event where 45 m (148 ft) of highway is impacted.

Based on the model results for the Ukumehame region, highway alignment alternative 4 is the least susceptible to potential flooding for the annual wave event where only 227 m (745 ft) of highway is impacted. Highway alignment alternative 2 was found to be the most susceptible to potential flooding in the Ukumehame region for an annual wave event where 835 m (2,741 ft) of highway is impacted. The modeled flooding under the bridge crossing region in Ukumehame is not included in the length of highway impacted assuming the bridge structure is higher than the flood waters. However, bridge supporting elements (i.e. piles, abutments, etc.) may be exposed to flood hazards and would require engineered protection against potential scour and hydraulic loading. Based on these modeling results, if fill is to be used instead of a bridge structure, the fill embankment may be exposed to wave-driven and passive flooding and would require bank protection through armoring or other engineered means.

It should be noted that these results are representative of an annually occurring (1-year return period) south swell wave event. Flooding may be more severe for less frequent but larger wave events combined with higher sea levels.

FEMA Flood Hazards and FIRMs

The FEMA coastal hazard zone along the study area consists of Zones VE and AE with base flood elevations (BFEs) between 1.8 m (6 ft) and 3.4 m (11 ft) along the shoreline. All alternative alignments cross over the AE Zone at the southeast end of the study area with BFEs between 1.82 m (6 ft) and 2.7 m (9 ft). These flood levels and zones were defined by the greater of the inundation from a 1-percent chance tsunami or hurricane storm surge under existing topography and sea level.

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1. INTRODUCTION

Sea Engineering, Inc. (SEI) has been contracted by WSP to conduct a sea level rise (slr) and wave inundation study for proposed roadway alignment alternatives along Honoapiilani Highway on Maui shown in Figure 1-1. The project area includes sections of the highway at Ukumehame and Olowalu where four (4) alternative highway realignments are being proposed shown in Figure 1-2. Due to the low-lying nature of this portion of coastline, the alignment alternative may be susceptible to future wave flooding with slr. This report summarizes the current slr projections and numerical modeling of wave induced flooding under a discrete future sea level for existing topography and each of the four (4) highway realignment alternatives.

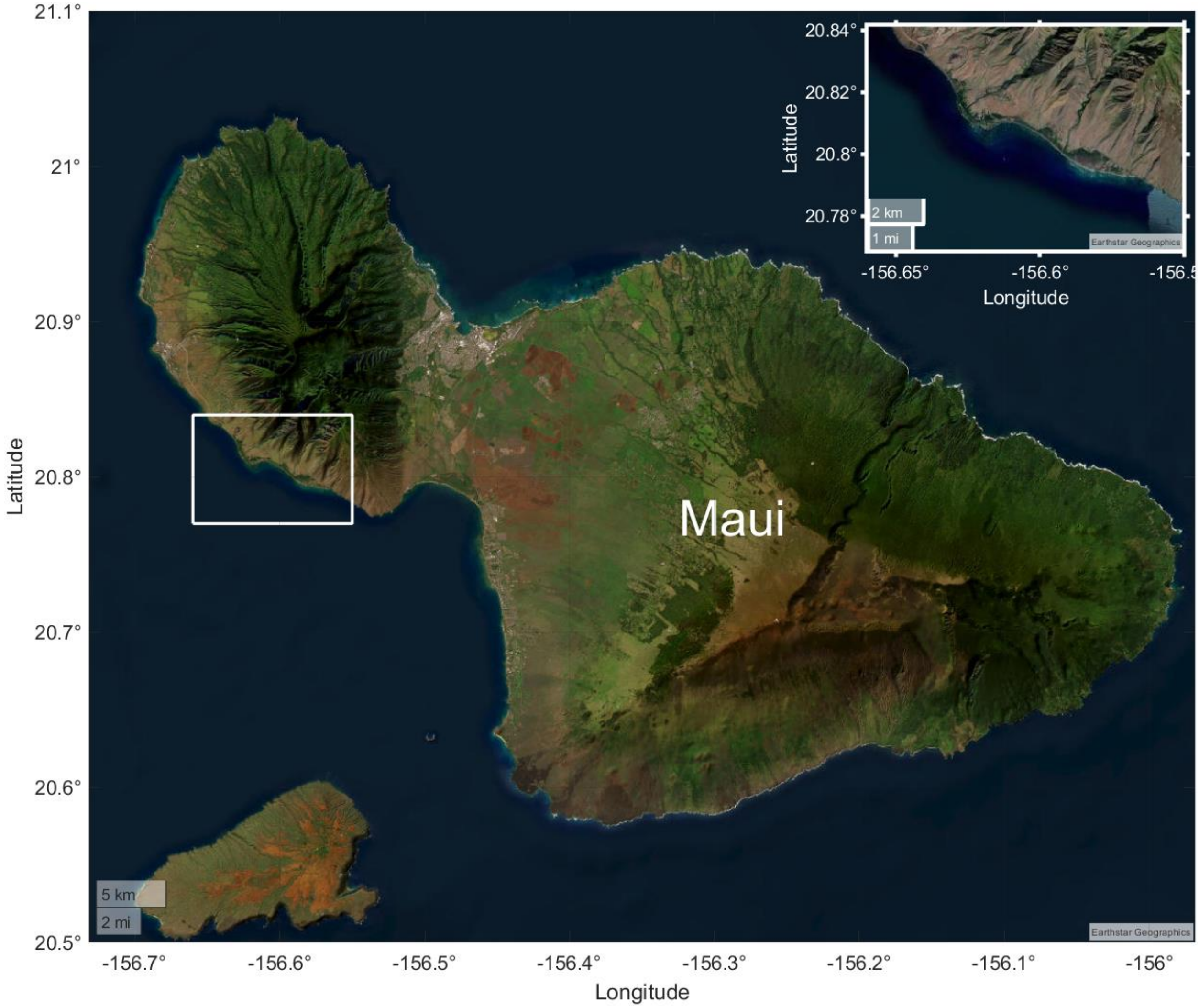

Figure 1-1. Project vicinity map

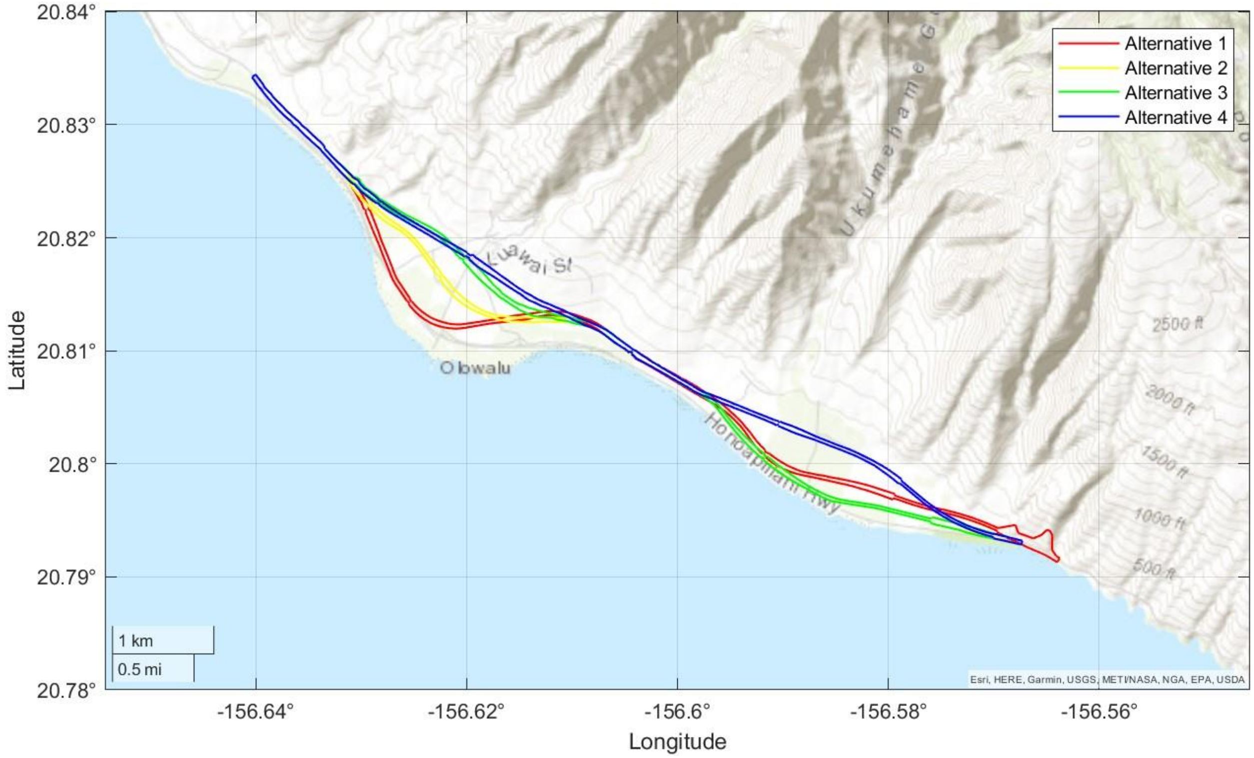

Figure 1-2. Proposed alternative highway realignments

2. SEA LEVEL RISE

2.1 Global Sea Level Rise Projections

Global mean sea level is the average height of the entire ocean surface. The present rate of global mean sea level change is +3.1 mm/yr (Sweet et al., 2022, Figure 2-1), where a positive number represents a rising sea level. Global mean slr has accelerated over preceding decades compared to the mean of the 20th century. Regional effects cause sea levels to increase in some parts of the planet while decreasing or remaining relatively stable in other areas. In the contiguous United States (U.S.), sea level has risen on average by 6.5 inches (in) since 1950 (Sweet et al., 2018). Factors contributing to the observed rise in sea level include melting of land-based glaciers and ice sheets and thermal expansion of the ocean water column.

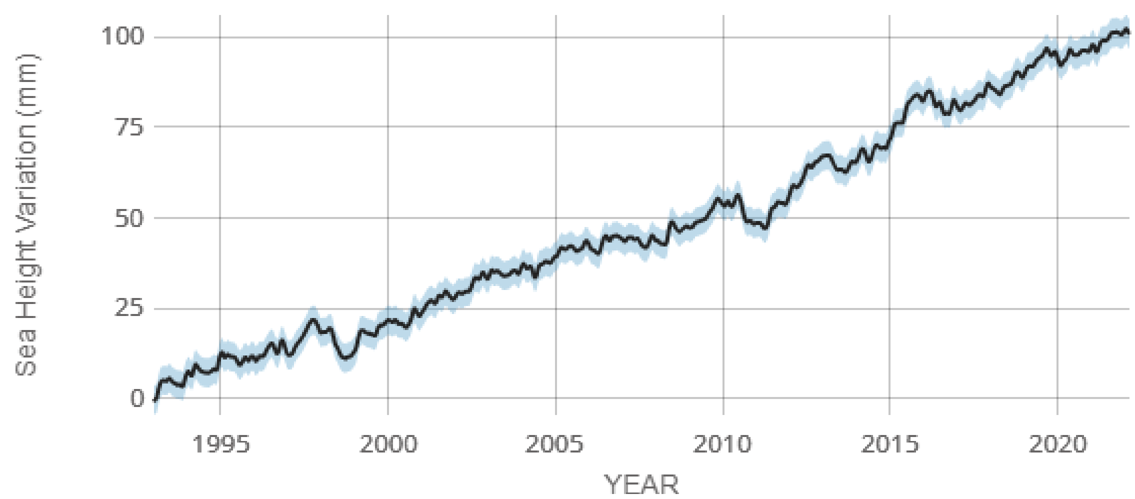

Figure 2-1. Global satellite sea level rise variability from 1993 to 2022 (Sweet et al.), where the black line shows the average sea level rise during the time period.

2.2 Maui Sea Level Rise Projections

Sweet et.al. (2017 and 2022) identify specific regions that are susceptible to a greater-than-average rise in sea level. Hawaii thus far has seen a rate of SLR (+1.55 mm/yr [0.06 in/yr]) less than the global average (+3.1 mm/year [0.12 in/yr]); however, this is expected to change in the future as Hawaii is in the "far-field" of the effects of melting land ice. This means that those effects have been significantly less in Hawaii compared to areas nearer to the ice melt. Over the next few decades, these effects will spread to Hawaii, which is then projected to experience a SLR greater than the global average.

The relative sea level trend for Kahului Harbor for the period of 1947 to present is shown in Figure 2-2 (NOAA, 2023). The relative sea level trend at Kahului Harbor is +2.22± 0.38 mm/yr (0.09± 0.01 in/yr). Figure 2-2 also shows interannual anomalies exceeding 15 cm (0.49 ft) in magnitude due to natural oceanic variability from processes such as the El Niño-Southern Oscillation (ENSO).

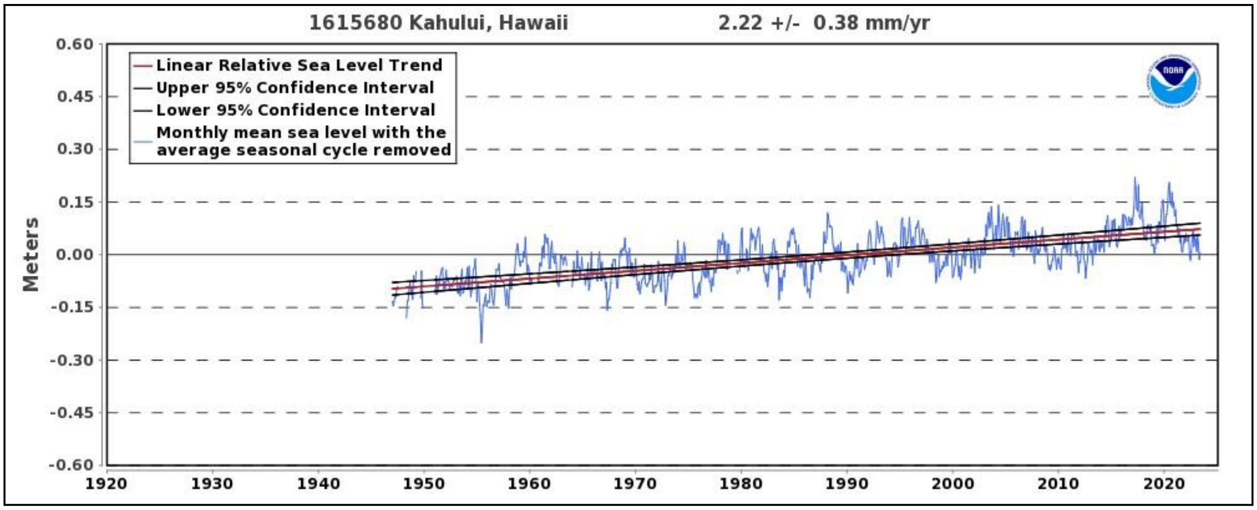

Figure 2-2. Mean sea level trend, Kahului Harbor, Station 1615680, 1947 to present (NOAA, 2023)

2.2.1 *IPCC AR6 - Kahului Sea Level Rise Projections*

The NASA slr projection tool[1] for the IPCC AR6 projections provides adjusted slr curves for individual tide stations around the globe. The IPCC AR6 slr curves for Kahului Harbor from 2020 to 2150 are shown in Figure 2-3 and Table 2-1. Projected timings of when slr reaches 0.98 m (3.2 ft) for each scenario are shown in Figure 2-4. Appendix A summarizes the background for the IPCC AR6 projections.

[1] https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=155&data_layer=scenario

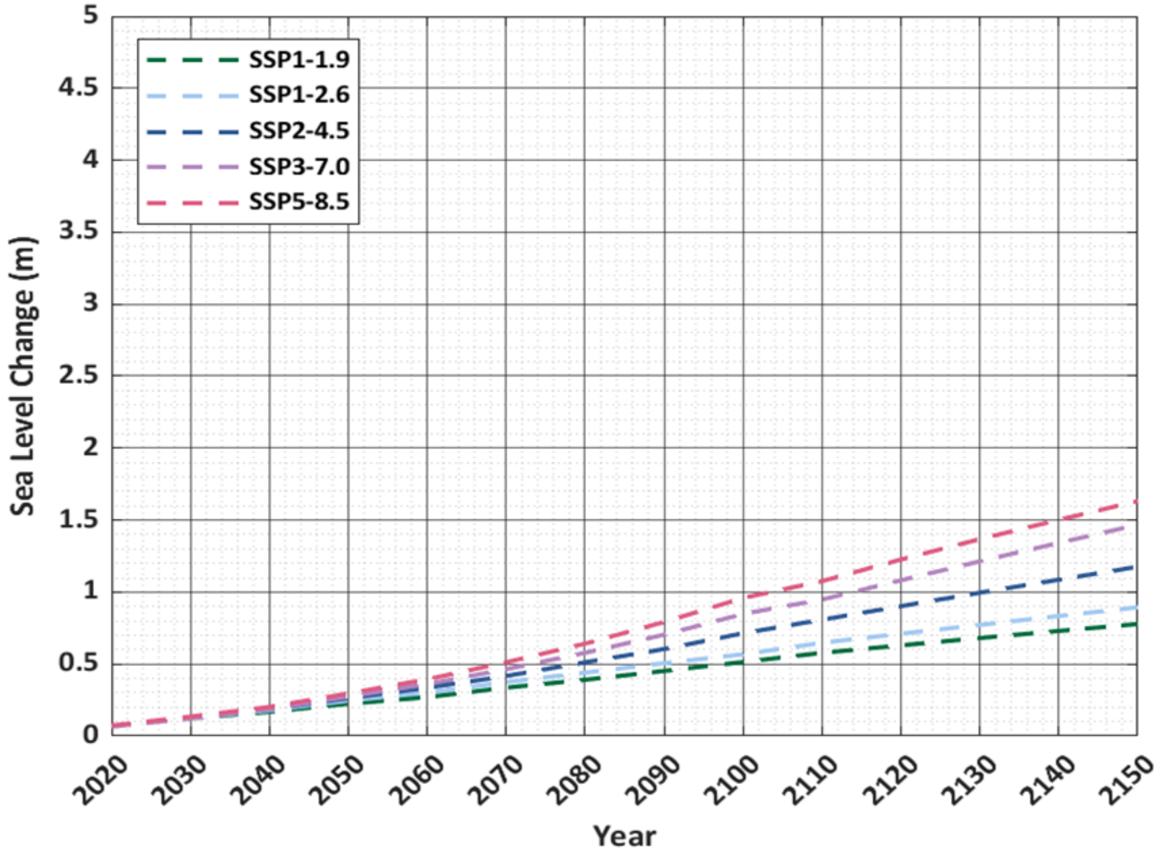

Figure 2-3. IPCC AR6 sea level rise projections for Kahului Harbor, 2020 to 2150 (IPCC, 2021)

Table 2-1. IPCC AR6 sea level rise projections for Kahului Harbor, 2020 to 2150 (IPCC, 2021)

Scenario/Year (m)	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140	2150
SSP1-1.9	0.07	0.12	0.17	0.22	0.27	0.34	0.39	0.45	0.51	0.58	0.63	0.68	0.73	0.78
SSP1-2.6	0.07	0.12	0.18	0.25	0.30	0.38	0.44	0.51	0.57	0.65	0.71	0.77	0.83	0.89
SSP2-4.5	0.07	0.12	0.19	0.26	0.34	0.42	0.51	0.60	0.71	0.81	0.90	1.00	1.09	1.18
SSP3-7.0	0.07	0.12	0.19	0.27	0.36	0.46	0.58	0.70	0.85	0.95	1.08	1.21	1.34	1.47
SSP5-8.5	0.07	0.14	0.20	0.30	0.39	0.51	0.64	0.79	0.96	1.08	1.23	1.37	1.50	1.63

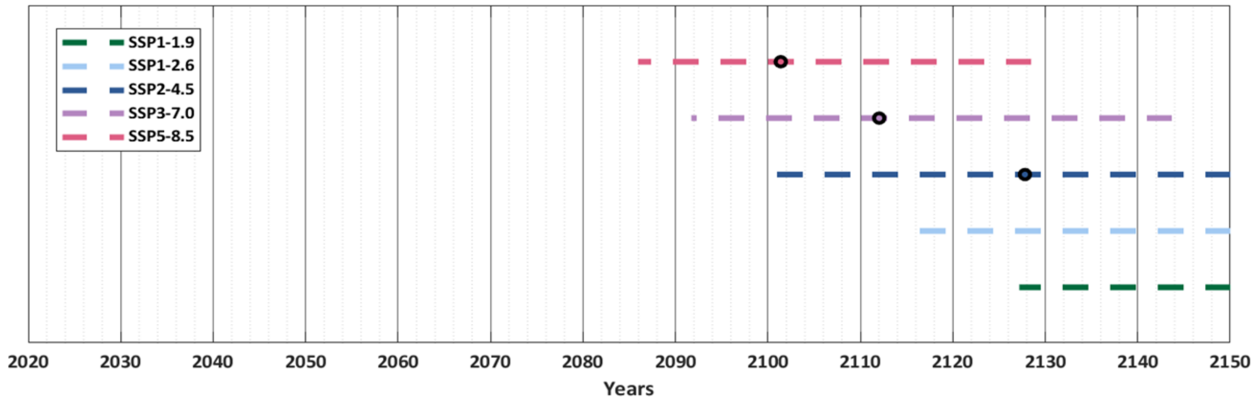

Figure 2-4. IPCC AR6 projected timings of 0.98 m (3.2 ft) of sea level rise for Kahului Harbor (IPCC, 2021)

2.2.2 *U.S. Interagency Task Force - Kahului Sea Level Rise Projections*

The NASA slr projection tool[2] for the Task Force projections provides adjusted slr curves for individual tide stations around the globe. The Task Force slr curves for Kahului from 2020 to 2150 are shown in Figure 2-5 and Table 2-2. Projected timings of when slr reaches 0.98 m (3.2 ft) for each scenario are shown in Figure 2-6. Appendix A summarizes the background for the Task Force projections.

[2] https://sealevel.nasa.gov/task-force-scenario-tool?psmsl_id=155

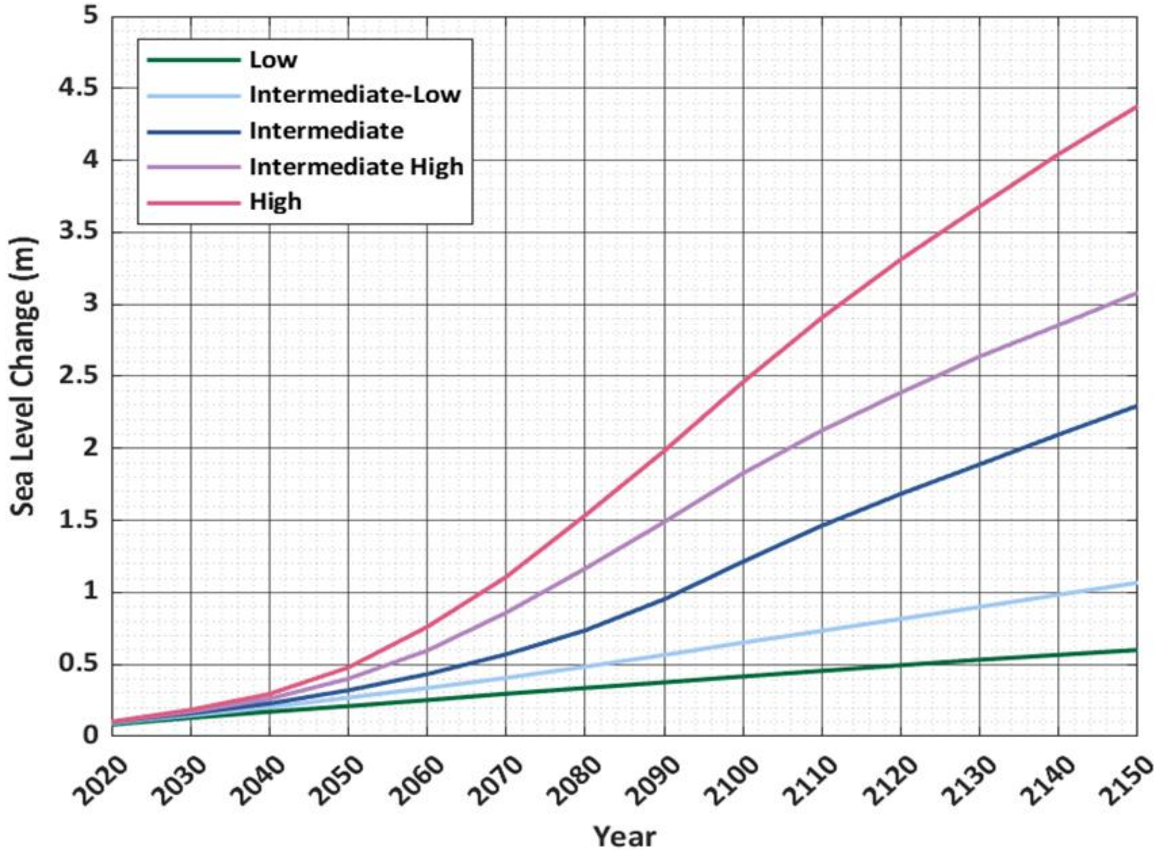

Figure 2-5. Kahului Harbor local mean sea level rise projections (adapted from Sweet et al., 2022)

Table 2-2. Kahului Harbor local mean sea level rise projections (adapted from Sweet et al., 2022)

Scenario/Year (m)	2020	2030	2040	2050	2060	2070	2080	2090	2100	2110	2120	2130	2140	2150
Low	0.08	0.13	0.17	0.21	0.25	0.30	0.34	0.38	0.42	0.46	0.49	0.53	0.57	0.60
Int-Low	0.09	0.15	0.20	0.27	0.34	0.41	0.48	0.57	0.65	0.73	0.82	0.90	0.98	1.07
Int	0.10	0.16	0.23	0.32	0.43	0.57	0.74	0.95	1.21	1.46	1.68	1.89	2.10	2.30
Int-High	0.10	0.17	0.26	0.40	0.60	0.86	1.17	1.49	1.83	2.12	2.39	2.64	2.86	3.08
High	0.10	0.18	0.29	0.48	0.76	1.11	1.53	1.98	2.46	2.91	3.31	3.68	4.04	4.38

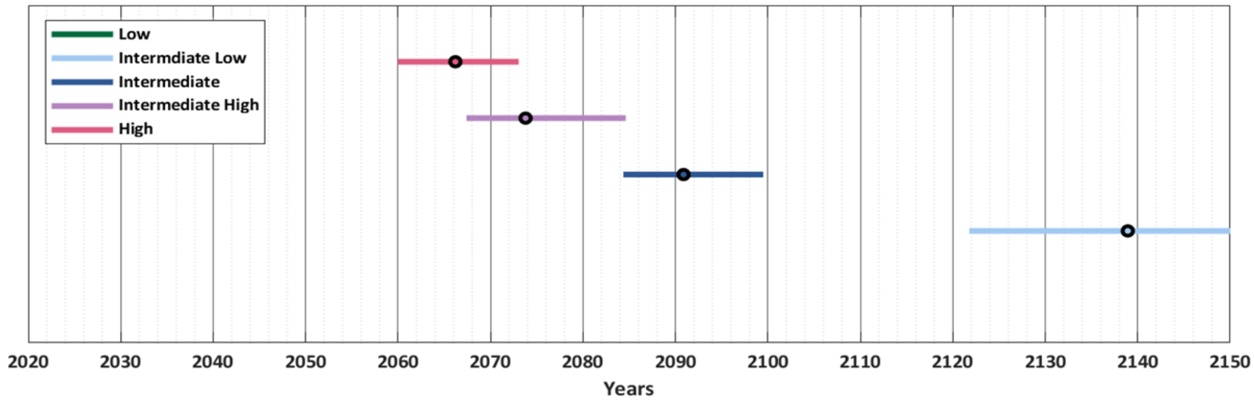

Figure 2-6. Task Force projected timings of 0.98 m (3.2) ft of sea level rise for Kahului Harbor (adapted from Sweet et al., 2022)

2.3 Guidance for Sea Level Rise Planning and Adaptation

While the slr projections described in the previous sections are based on the most current scientific models and measurements, discretion is necessary when selecting the appropriate planning scenario(s). Selecting the appropriate sea level change projection(s) is a function of many parameters, including but not limited to topography, coastal setting, criticality of infrastructure, potential for resilience, budget, and function.

In 2017, the National Oceanic and Atmospheric Administration (NOAA) released Technical Report NOS CO-OPS 083 describing global and regional SLR scenarios for the U.S. The report emphasizes that coastal planners making critical decisions should weigh several factors when choosing which SLR scenario to use, such as the type of decision to be made, expected future performance, planning horizon, and overall risk tolerance, including the criticality of the asset and/or the size and vulnerability of the exposed population (Hall et al., 2016). For example, when designing a patio for a home or a bike path, a lower SLR scenario might be used for the design as it does not support any critical functions and may have a higher risk tolerance. In contrast, when designing a hospital or power plant with a low-risk tolerance and a high criticality of the asset, a higher SLR scenario might be selected to design for future conditions. Scenarios help serve as a starting point for on-the-ground coastal preparedness planning and risk management processes needed to ensure that U.S. coastal communities (and their economies) remain vibrant and resilient to ongoing and future changes in sea level.

In 2018, SEI participated on the Hawaiian Islands and Affiliated Pacific Islands regional climate assessment team, which contributed to the 4th National Climate Assessment (USGCRP, 2018). The consensus from the regional team, which included representatives from NOAA, the U.S. Geological Survey (USGS), and the University of Hawaii (UH), was that the 2017 NOAA *Intermediate-High* scenario projections are recommended for planning purposes in Hawaii.

This was revised in an important conclusion of the 2022 report. The current report indicates that NOAA's revised *Intermediate* rate is recommended for planning and design purposes in Hawaii.

According to the new IPCC AR6 report, the most aggressive, plausible slr scenario is the SSP5-8.5. On Maui, SSP5-8.5 projects that the sea level will rise 0.30 m (1.0 ft) by 2050, 0.50 m (1.7 ft) by 2070, and 0.96 m (3.2 ft) by 2100.

The Task Force's *Intermediate* scenario projects sea level on Maui will rise 0.32 m (1.1 ft) by 2050, 0.57 m (1.9 ft) by 2070, and 1.21 m (4.0 ft) by 2100.

The *Intermediate-High* scenario projects 0.40 m (1.3 ft) by 2050, 0.86 m (2.8 ft) by 2070, and 1.83 m (6.0 ft) by 2100.

3. HAWAII SEA LEVEL RISE FLOODING DATASETS

Coastal hazards associated with future sea level rise include flooding of low-lying areas, wave-driven overland flooding, and coastal erosion. Datasets are available for the Hawaiian Islands and West Maui specifically which utilize available bathymetric/topographic data, numerical models, and empirical formulas to quantify coastal hazards associated with future sea level rise. These datasets provide a useful tool for planners and engineers in the early stages of planning and design of infrastructure near the shoreline. Two datasets available for the study area include the *Hawaii Sea Level Rise Exposure Area* and the *West Maui Wave-Driven Flooding With Sea Level Rise*. The following subsections summarize the background of these datasets and how they were derived.

The focus of this study is to perform higher-resolution site-specific inundation modeling to better define the hazards associated with passive and annual high wave flooding for 3.2 ft of slr. The site-specific modeling analysis in this study accounts for the change in topography for each highway alignment alternative whereas the datasets summarized below only account for existing topography. Additionally, the available datasets were developed for large regional areas around the State and the West Maui shoreline and may not capture localized effects that would likely be resolved by a site-specific analysis.

3.1 Hawaii Sea Level Rise Exposure Area

The Hawaii Sea Level Rise Vulnerability and Adaptation Report (State of Hawaii, 2017) discusses the anticipated impacts of projected future slr on coastal hazards, and the potential physical, economic, social, environmental, and cultural impacts of slr in Hawaii. The report concluded that 3.2 ft of slr may have substantial impacts on the island of Oahu. A key component of the report was a numerical modeling effort by the University of Hawaii Coastal Geology Group (UHCGG) to estimate the potential impacts that a 0.15 (0.5), 0.34 (1.1), 0.61 (2.0), and 0.98 m (3.2 ft) rise in sea level would have on coastal hazards including passive flooding, annual high wave flooding, and coastal erosion. The footprints of these three hazards were combined to map the projected extent of chronic flooding due to slr, referred to as the Sea Level Rise Exposure Area (SLR-XA). The modeling results can be found via the State of Hawaii Sea Level Rise Viewer [3]. The SLR-XA hazard line was used in the preliminary phase of the project to aid in locating the alternative highway alignments.

3.1.1 *SLR-XA Passive Flooding Hazard*

The UHCGG modeled passive flooding using a modified "bathtub" method (Anderson et al., 2018). The method utilizes a detailed digital elevation model (DEM) of the backshore, typically derived from aerial light detection and ranging (LiDAR) data. Elevations within the DEM that are below the elevation of the combined slr and local mean higher high water (MHHW) are considered passive flood areas. Passive flood areas that are connected to the ocean are considered "marine inundation" areas, while areas not connected to the ocean are considered "groundwater inundation" areas. Figure 3-1 shows an idealized cross-shore profile of passive flooding used in the SLR-XA model.

[3] https://www.pacioos.hawaii.edu/shoreline/slr-hawaii/

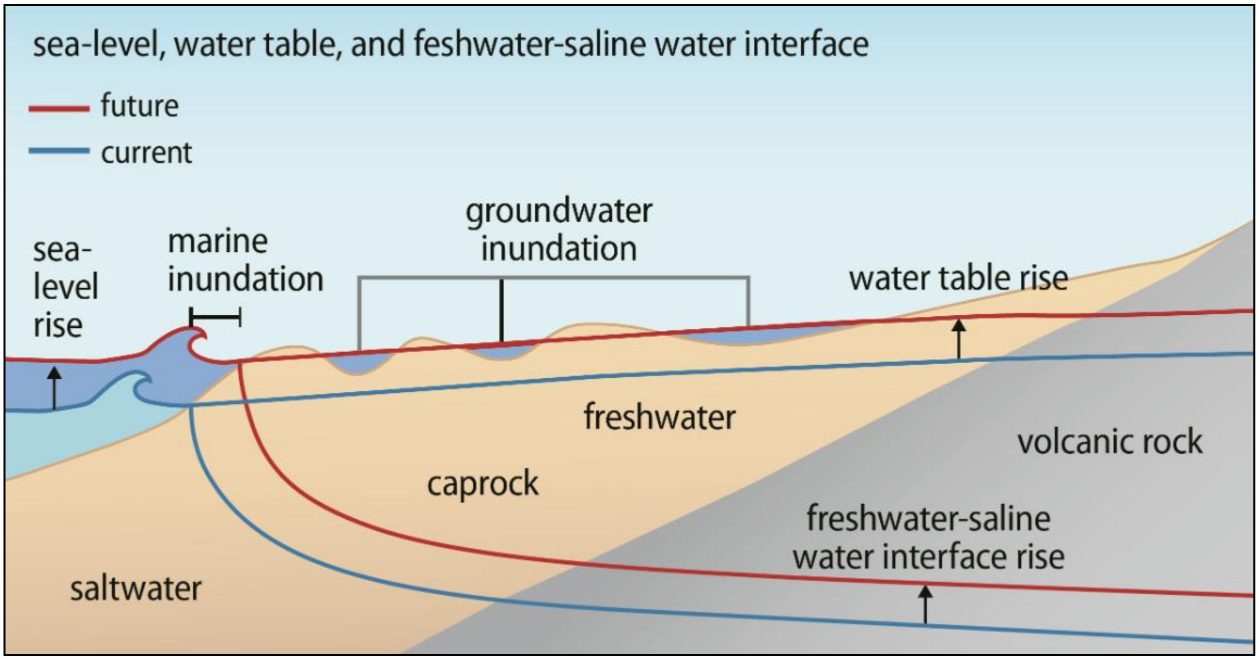

Figure 3-1. Cross-shore profile schematic of SLR-XA passive marine and groundwater flooding (UHCGG, 2017)

3.1.2 *SLR-XA Annual High Wave Flooding Hazard*

The annual high wave flooding model propagates the maximum annually recurring wave, calculated from historical wave buoy data, over the reef and to the shore along 1-dimensional cross-shore profiles spaced 20 meters (m) apart. Topography and bathymetry for each profile was extracted from a 1-m digital elevation model. Model output for areas between the 1-dimensional profiles were interpolated and compiled in a 5-m map grid. The model depicts the spatial extent of inundation that is greater than 10 centimeters (cm) in depth. Figure 3-2 illustrates an idealized cross-shore profile schematic of the SLR-XA annual high wave flooding.

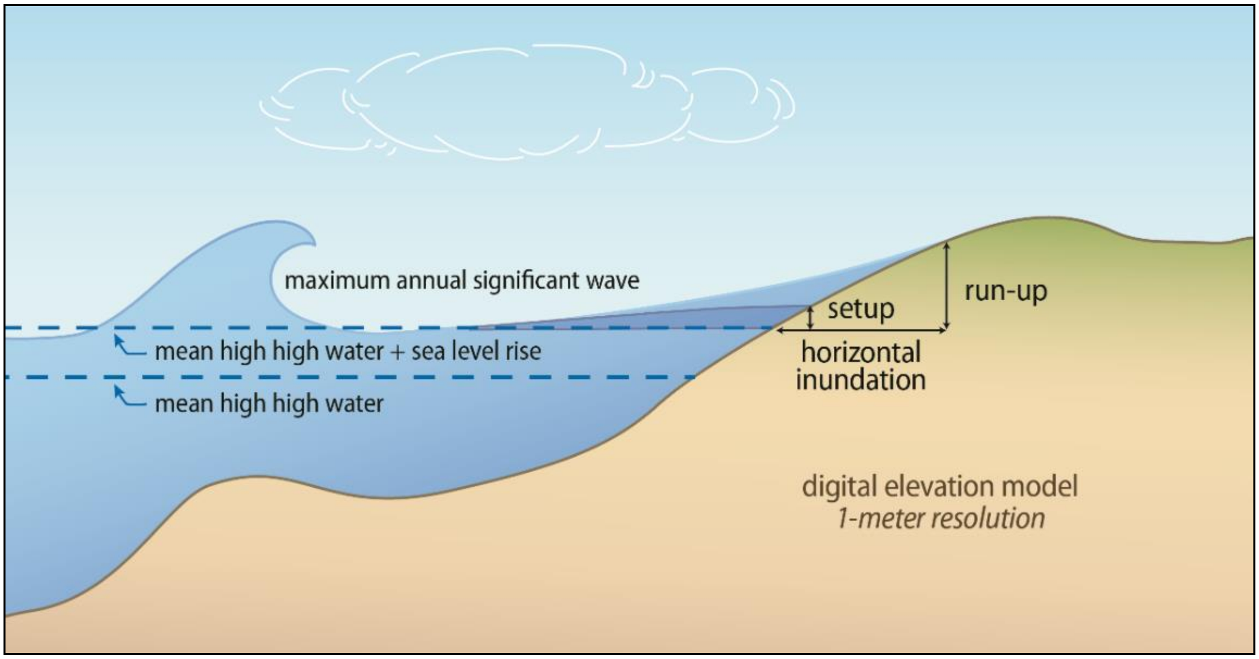

Figure 3-2. Cross-shore profile schematic of SLR-XA annual high wave flooding (UHCGG, 2017)

3.1.3 *SLR-XA Coastal Erosion Hazard Area*

The erosion model (Anderson, 2015) presented in the PacIOOS Sea Level Rise Viewer is based on accepted sea-level rise scenarios. The prediction of 3.2 ft of global mean slr by 2100 is from the aggressive IPCC AR5 sea level curve. This curve represents the upper-end projection from the AR5. This is similar to the upper-end projection in the AR6 report. The erosion model estimates shoreline change resulting from a combination of the historic erosion pressures on the coastline, rising water levels, and the influence of additional water level on coastal erosion processes.

The historic erosion rates are based on shoreline location measurements collected at individual transect located 20 meters apart on the coastline. These measurements capture the real changes occurring in each transect's unique environment. Though projections of historic erosion rates may not be accurate predictions of the distant future, they are accurate for past changes at each individual transect's unique environment. These rates reflect the shoreline changes associated with historic changes in sea level, and do not include any influences of accelerating rates of slr as expected in future decades and centuries.

Sea level rise results in a change to the horizontal shoreline location based purely on higher water levels moving up and typically mauka along the coastal profile. The model includes a change of water level based on the historic rate of sea level (not the projected curves) extrapolated to the year 2100.

Projected erosion impacts as a response to rising sea levels, the amount of rise in excess of historic rates, assumes that coastal changes in the nearshore, shoreline, and backshore (to the maximum extent of erosion) are occurring in mobile sandy substrate (Figure 3-3) (Davidson-Arnott, 2005). The model's implicit assumption is that sand moves freely along the affected dry and submerged profile, allowing the entire system to respond as a whole to the effects of a rising sea level. Actual shoreline migration may follow a different path and pace in some of the project areas, as some sections of Maui's coastline do not closely match these assumptions. Within the project area, there are shallow fringing reefs in the nearshore, and clay and rock may be present within the backshore, mauka of and sometimes beneath the sandy beach.

The combined result of these inputs (Figure 3-4) is the erosion hazard line, presented in the PacIOOS viewer.

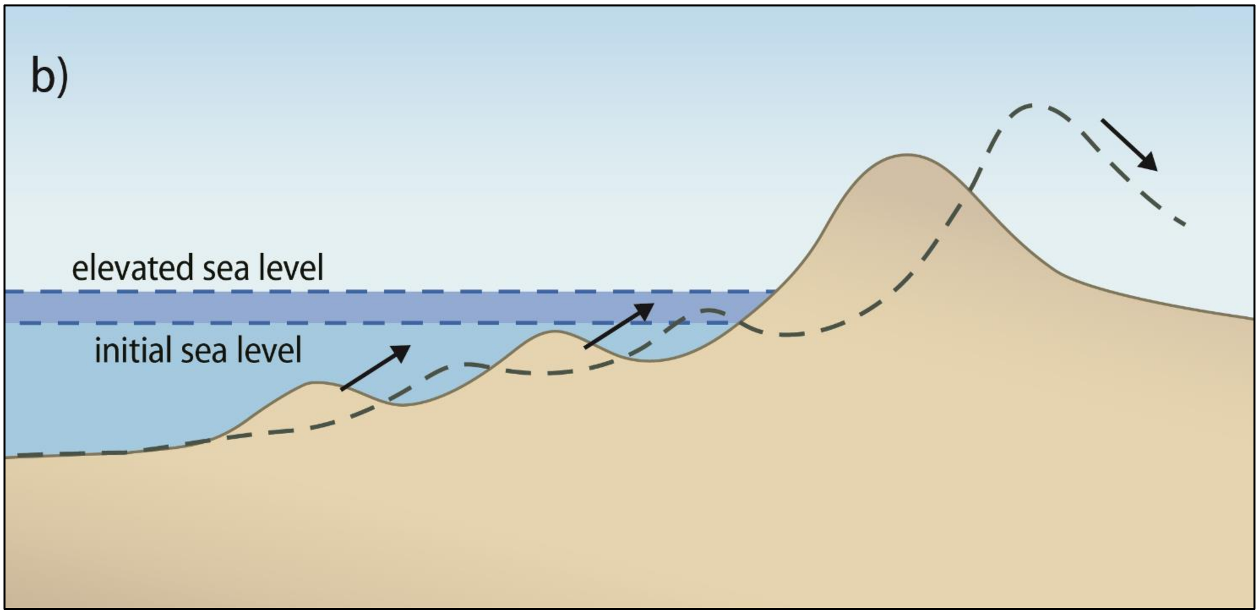

Figure 3-3. Example of Davidson-Arnott Conceptual Model for Shoreline Change Under Rising Sea Levels

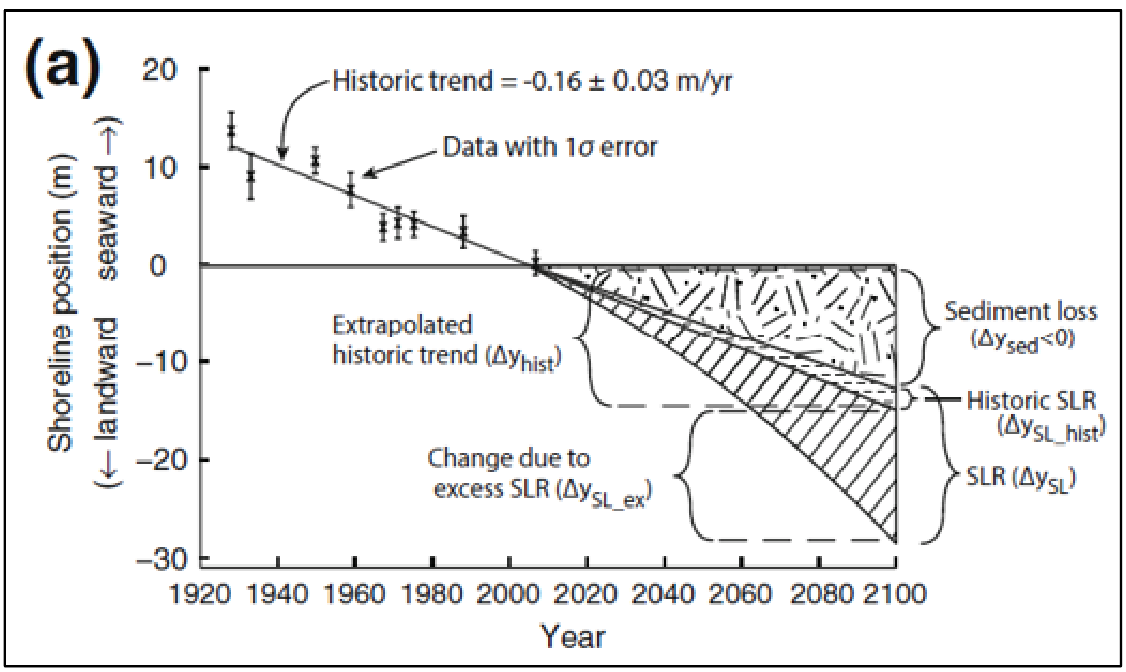

Figure 3-4. Graphic representation of the erosion model components from Anderson, et al., 2015

Below is the list of assumptions and limitations, as presented on PacIOOS website, which should be considered when reviewing the location of the erosion hazard line:

- Existing seawalls or other coastal armoring in the backshore* (may over-predict in these cases)
- Increasing wave energy across the fringing reef with slr (may under-predict in these cases)
- Possible changes in reef accretion and nearshore sediment processes with slr (may over-predict or under-predict based on the case)
- Possible changes to sediment supply from future shoreline development and engineering, such as construction or removal of coastal armoring or other coastal engineering. (may over-predict [e.g. beach nourishment] or under-predict [e.g. sand mining] based on the case)
- Where a beach was lost to erosion fronting coastal armoring, historical shoreline change rates used in the coastal erosion model were calculated using historical shoreline positions up to and including the first shoreline indicating no beach.

3.1.3.1 Evaluating the Erosion Hazard Line

The model results represent a valuable tool for assessing potential erosion along a coastline under the pressure of rising water levels. Understanding that the model may over or underpredict erosion potential based on project area site characteristics allows for prudent use of the results in planning and design efforts.

Using the aggressive AR5 and AR6 slr curve to establish 3.2 ft of slr by 2100 helps to provide a conservative estimate for water level at that point in time. Combining the conservative estimate for water level with a conceptual model to assess potential erosion threat along the project area's coastline provides a useful tool to include in planning.
Using the erosion hazard line (example in Figure 3-5) as a design feature, a location to stay mauka of where possible, is both prudent and proactive for long-range planning that targets the end of century.

Figure 3-5. Erosion Hazard Model projection for shoreline location with 3.2 ft of slr at Ukumehame

3.1.4 *SLR-XA Combined Hazard Exposure Area*

The SLR-XA is an overlay of the combined exposure to passive flooding, annual high wave flooding, and coastal erosion as shown in Figure 3-6 and does not include the interactive nature of these hazards that occurs in reality.

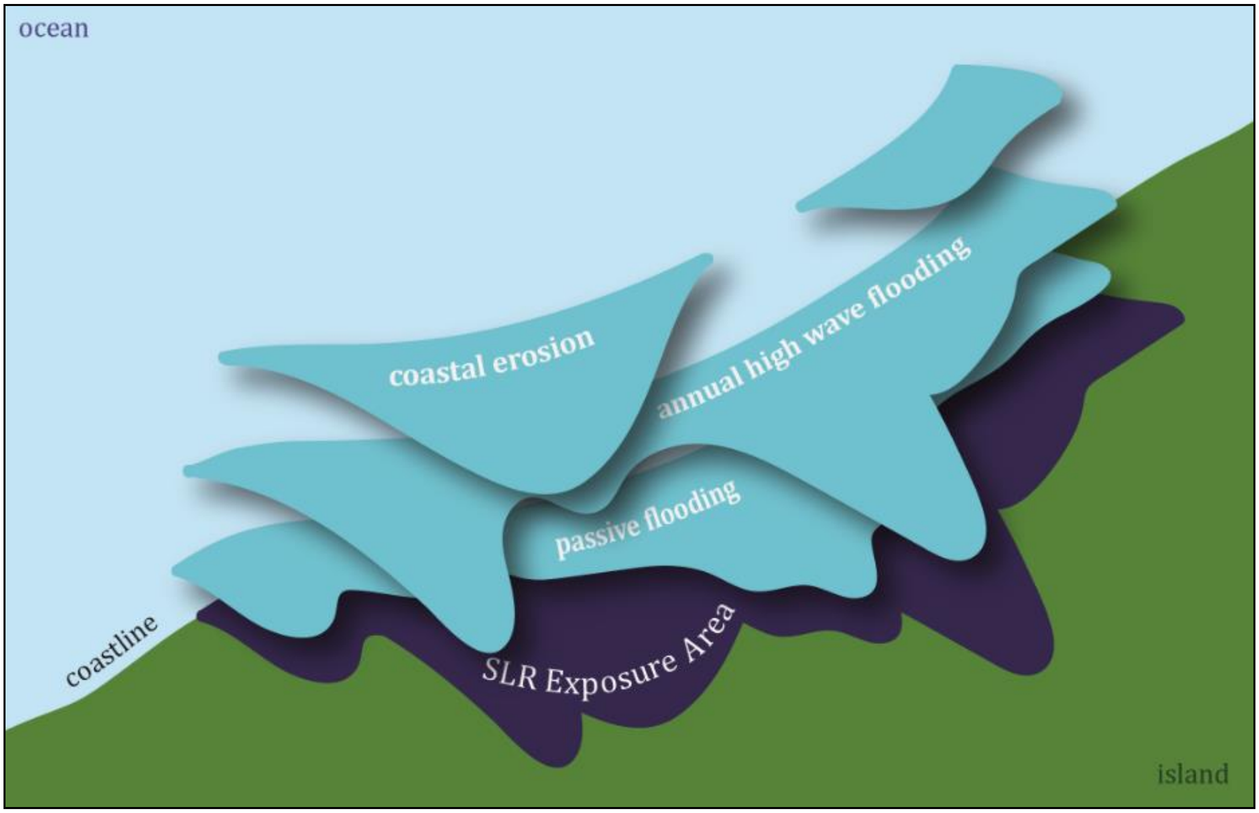

Figure 3-6. Schematic of combined exposure area consisting of passive flooding, annual high wave flooding, and coastal erosion (UHCGG, 2017)

3.2 West Maui Wave-Driven Flooding with Sea Level Rise

The West Maui Wave-Driven Flooding with Sea Level Rise dataset[4] available through PacIOOS, provides additional insight into the effects of wave-driven flooding combined with sea level rise along the West Maui coastline. The tool provides flood extent and flood depths for sea level rise values of 0.0, 0.3 (1.0), 0.6 (2.0), 1.0 (3.3), and 2.0 m (6.6 ft) as well as for wave conditions defined as minimum, annual high, and maximum wave conditions. The modeled flooding is associated with a combination of waves from the north and south pacific swell regimes for each wave type, and the flood layer can be further broken out by specific swell direction if desired. The modeled flooding was simulated by two (2) Boussinesq Ocean and Surf Zone (BOSZ; Roeber and Cheung, 2012) model domains with 5 m resolution encompassing the West Maui coastline (see Figure 3-7).

[4] https://www.pacioos.hawaii.edu/shoreline/slr-westmaui/

The West Maui tool provides improved estimates of wave-driven flooding with slr compared to SLR-XA because it used a 2D modeling approach instead of a 1D approach and includes additional wave conditions. However, the data is valid for existing ground only and does not include any proposed ground changes for this project. The high-resolution site-specific modeling for this study utilizes a similar modeling framework as this tool but utilizes a higher resolution model domain and incorporates the proposed ground changes for each of the four (4) proposed highway alignments to better quantify the flooding hazard along the project shoreline.

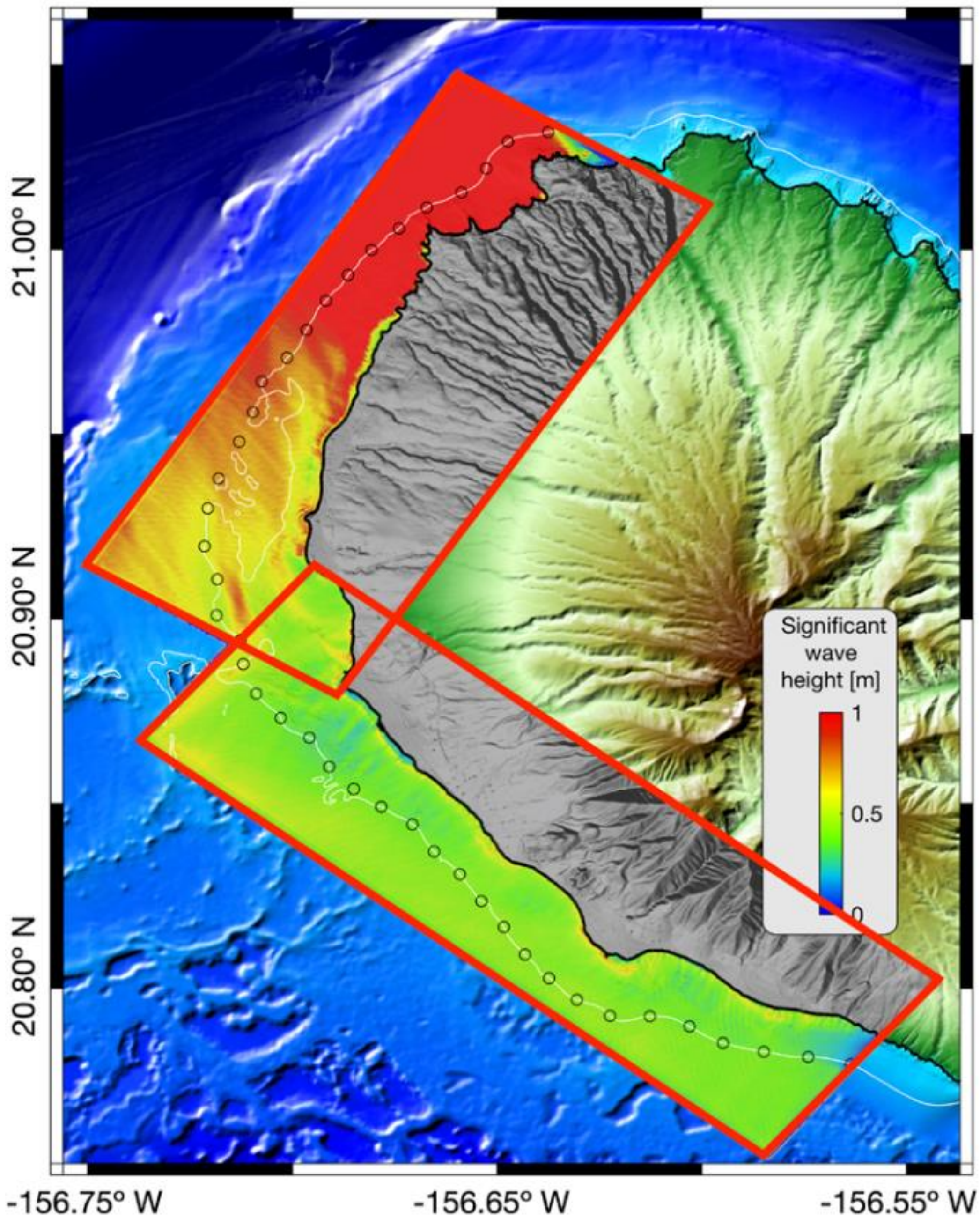

Figure 3-7. BOSZ model domains used for the West Maui Wave-Driven Flooding Tool

4. WAVE CLIMATE

Numerical wave inundation models require offshore wave parameters as primary boundary conditions. This section summarizes the general wave climate in Hawaii and provides background on the specific wave conditions pertinent to the study shoreline to be used as input to the numerical modeling.

4.1 General Wave Climate

The wave climate in Hawaii is dominated by long period swell generated by distant storm systems, by relatively low amplitude, short period waves generated by more local winds, and the occasional bursts of energy associated with intense local storms. Typically, Hawaii receives five general surface gravity wave types: 1) northeast trade wind waves, 2) southeast trade wind waves 3) South Pacific swell, 4) North Pacific swell, and 5) Kona wind waves. The dominant swell regimes for Hawai‘i are shown in Figure 4-1.

Trade wind waves occur throughout the year and are most persistent from April to September when they usually dominate the local wave climate. They result from the strong and steady trade winds blowing from the northeast quadrant over long fetches of open ocean. Trade wind deepwater waves are typically between 3 to 8 ft high with periods of 5 to 10 seconds, depending upon the strength of the tradewinds and how far the fetch extends east of the Hawaiian Islands. The direction of approach, like the trade winds themselves, varies between north-northeast and east-southeast and is centered on the east-northeast direction. The study areas are well sheltered from the direct approach of trade wind waves by the island itself.

During the winter months in the northern hemisphere, strong storms are frequent in the North Pacific in the mid latitudes and near the Aleutian Islands. These storms generate large North Pacific swells that range in direction from west-northwest to northeast and arrive at the northern shores of the Hawaiian Islands with little attenuation of wave energy. These are the waves that have made surfing beaches on the north shores of the island of Oahu and Maui famous. Deepwater wave heights often reach 15 ft and in extreme cases can reach 30 ft. Periods vary between 12 and 20 seconds, depending on the location of the storm. The project site is sheltered by the island of Maui itself for northeasterly swell and by the island of Molokai for swell approaching from the northwest. However, even with island sheltering, the project site is still directly and indirectly exposed to North Pacific swell.

South Pacific swell is generated by storms in the southern hemisphere and is most prevalent during the summer months of April through September. Traveling distances of up to 5,000 miles, these waves arrive with relatively low deepwater wave heights of 1 to 4 ft and periods of 14 to 20 seconds. Depending on the positions and tracks of the southern hemisphere storms, south swells approach from between the southeasterly and southwesterly directions. The study areas are directly exposed to south swell approaching from the south-southwest to southwest directions. More southerly swell would be partially blocked by the island of Kahoolawe.

Kona storm waves can also directly and indirectly approach the study areas; however, these waves are relatively infrequent, occurring only about 10 percent of the time during a typical year. Kona storm waves typically range in period from 6 to 10 seconds with heights of 5 to 10 ft, and approach from between the southwest and west directions. Deepwater wave heights during the severe Kona storm of January 1980 were about 17 ft. The study areas are directly exposed to Kona storm waves that approach from the west-southwest and south-southwest between the islands of Lanai and Kahoolawe.

Severe tropical storms and hurricanes have the potential to generate extremely large waves, which in turn could potentially result in large waves at the study areas. Recent hurricanes impacting the Hawaiian Islands include Hurricane Iwa in 1982 and Hurricane Iniki in 1992. Iniki directly hit the island of Kauai and resulted in large waves along the southern and western shores of all the Hawaiian Islands. Damage from these hurricanes was extensive.

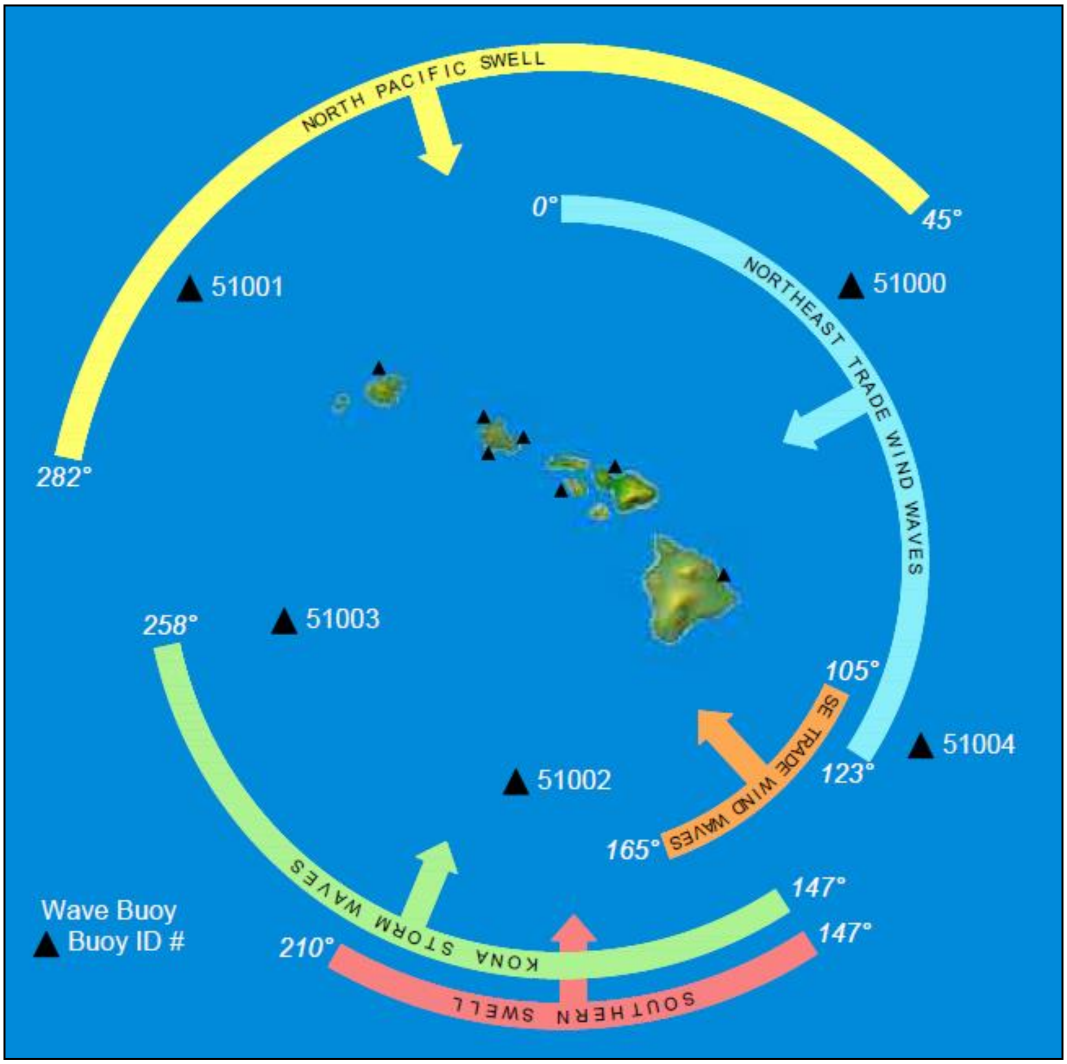

Figure 4-1. Hawai‘i dominant swell regimes

4.2 SLR-XA Annual Waves

For this study, annually recuring wave data used in the Sea Level Rise Exposure Area (SLR-XA) model framework is used to define the wave conditions offshore of the study areas. This wave data is defined along, approximately, the 30 m (98 ft) depth contour. Figure 4-2 shows the locations of the SLR-XA annual wave data relative to the study areas. The corresponding wave parameters, including significant wave height (*Hs)*, peak period (*Tp)*, and direction (*Dir.)*, are listed in Table 4-1. The SLR-XA wave data for this region is representative of an annually recuring south swell event.

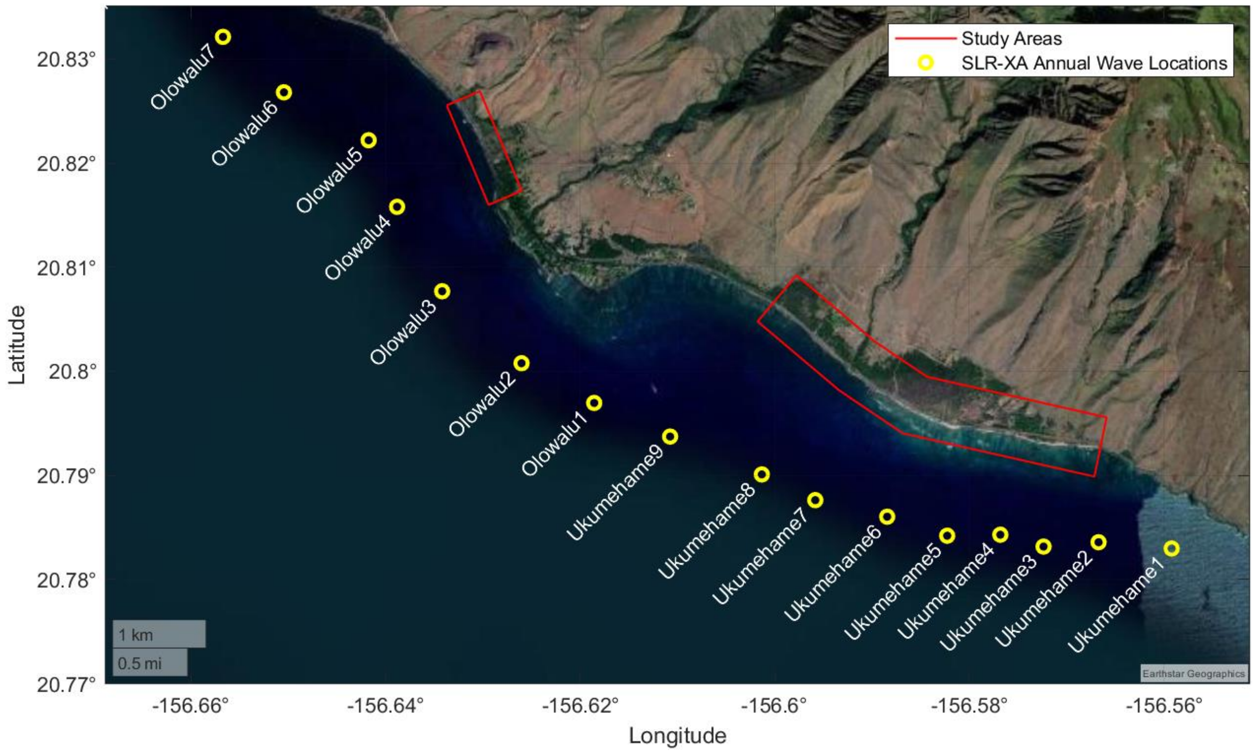

Figure 4-2. SLR-XA annual offshore wave locations relative to the study areas

Table 4-1. SLR-XA annual offshore wave parameters

Location ID	Hs (m)	Tp (s)	Dir (deg. TN)
Ukumehame1	0.718	16.4	215
Ukumehame2	0.790	16.4	212
Ukumehame3	0.799	16.4	212
Ukumehame4	0.712	16.4	203
Ukumehame5	0.722	16.4	203
Ukumehame6	0.931	16.4	207
Ukumehame7	0.942	16.4	207
Ukumehame8	0.946	16.4	207
Ukumehame9	0.983	16.4	208
Olowalu1	0.994	16.4	209
Olowalu2	1.001	16.4	207
Olowalu3	1.030	16.4	215
Olowalu4	0.926	16.4	218
Olowalu5	0.922	16.4	218
Olowalu6	1.068	16.4	213
Olowalu7	1.010	16.4	200

5. WAVE INUNDATION MODELING

Coastal flooding is generally a function of the tide level, wind setup, wave setup, and wave height at the shoreline. For fringing reef type environments, coastal flooding can also be caused by infragravity waves which can create elevated water levels at the shoreline during wave events particularly in steep reef environments. These are long waves with periods in the range of 30 to 300 seconds and are primarily caused by wave breaking on the reef flat. To accurately simulate wave-driven flooding in these environments, a sophisticated computer model capable of resolving all these phenomena at high resolution is required.

For this study the XBeach non-hydrostatic (XBeach-NH) numerical model was chosen to simulate nearshore wave propagation and wave-driven overland flooding of the study area. XBeach is a physics-based open-source numerical wave model originally developed to simulate hydrodynamic and morphological processes along sandy shorelines. The XBeach-NH module (Stelling and Zijlema, 2003) computes the depth-averaged flow due to waves and currents using the non-linear shallow water equations and includes a non-hydrostatic pressure term. The governing equations are valid from intermediate to shallow water and can simulate most of the phenomena of interest in the nearshore zone and in harbor basins, including shoaling and refraction over variable bathymetry, reflection and diffraction near structures, energy dissipation due to wave breaking and bottom friction, breaking-induced longshore/cross-shore (“rip”) currents, and harbor oscillations. XBeach-NH is a phase resolving model, meaning that wave crests and troughs are modeled and propagated in time and space.

5.1 Model Setup

Three (3) individual XBeach-NH model grids were developed to encompass the study areas and proposed roadway alignments along the shoreline. The three model grids are labeled as Region 1, 2 and 3 and shown in Figure 5-1. The model topography and bathymetry were adapted from the USACE SHOALS LiDAR dataset and the *Continuously Updated Digital Elevation Model (CUDEM) - Ninth Arc-Second Resolution Bathymetric-Topographic Tiles for the Hawaiian Islands*. Each model has a spatial resolution of 2 m (6.6 ft). For each of the three model domains, five (5) model topography were developed to represent existing conditions and alternative highway alignments 1 through 4. Change in ground elevation for each highway alternative was provided by WSP and incorporated into each of the model domains. Drainage culverts and bridge/causeway areas within each alignment were not adjusted and left as the existing ground level to allow modeled flood waters to pass freely through these areas. Road and bridge deck elevations for these areas are not included in the model with the assumption that modeled flood waters can pass freely under the proposed bridge structures. The model topography uses a bare-earth digital elevation model where buildings and vegetation are not included. Ground elevation for these areas are interpolated using the surrounding ground levels. The model does not account for flooding/drainage through underground utilities or groundwater intrusion. Erosion is also not included in the model.

The offshore wave boundary conditions for each model domain were defined by the SLR-XA annually recuring wave parameters (see Section 4.2). This boundary condition represents a spatially varying time series of the water surface elevation at the 30 m (98 ft) depth contour. Still water level input to the model is the combination of the mean higher high water (mhhw) 0.35 m

(1.1 ft) and slr of 0.98 m (3.2 ft) above mean sea level (msl) for a total still water input of 1.33 m (4.3 ft) above msl. This is representative of high tide conditions for a discrete future sea level.

The model simulation time frame is set to produce a minimum of 500 wave cycles to propagate through the model domain. This corresponds to a simulation time of approximately 2.3 hours after an initial spin-up model time of 30 min. Raw output from the model simulations includes the spatially varying water surface elevation throughout the model domain at set time intervals as well as statistical water surface elevation over the entire simulation time frame. The statistical output includes the mean, variance, maximum, and minimum water surface elevation and depth-averaged flow velocity throughout the model domain.

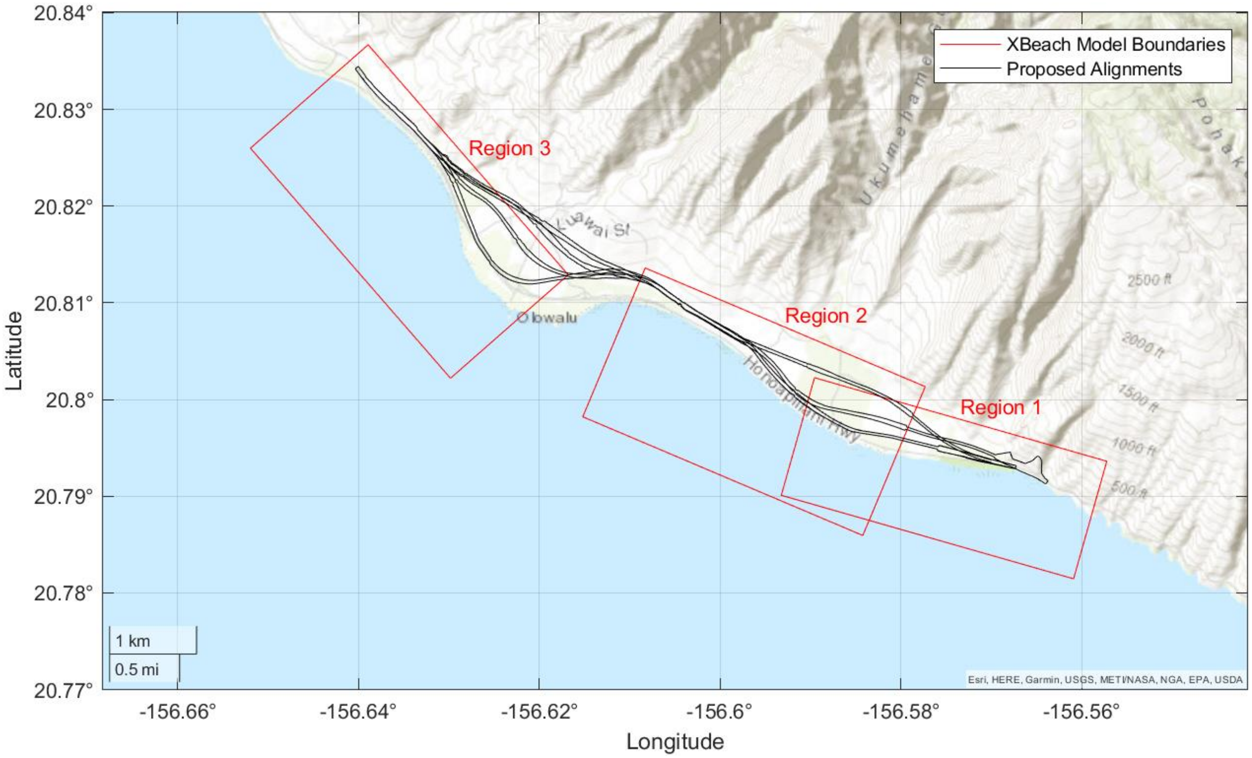

Figure 5-1. XBeach model boundaries relative to proposed alignment areas

5.2 Model Output

Snapshots of the water surface elevation mid-way through the simulation are shown in Figure 5-2, Figure 5-3, and Figure 5-4 for the Region 1, 2, and 3 model domains, respectively. The processed results from regions 1 and 2 are combined to provide continuous results for the stretch of shoreline covered by these regions. Overlapping areas use the maximum flood depths/elevations from either domain. The output area for regions 1 and 2 is identified as "*Ukumehame"* and region 3 is identified as "*Olowalu."* Appendices B through F show the modeled maximum flood depth and elevation for each of the five cases simulated for each area.

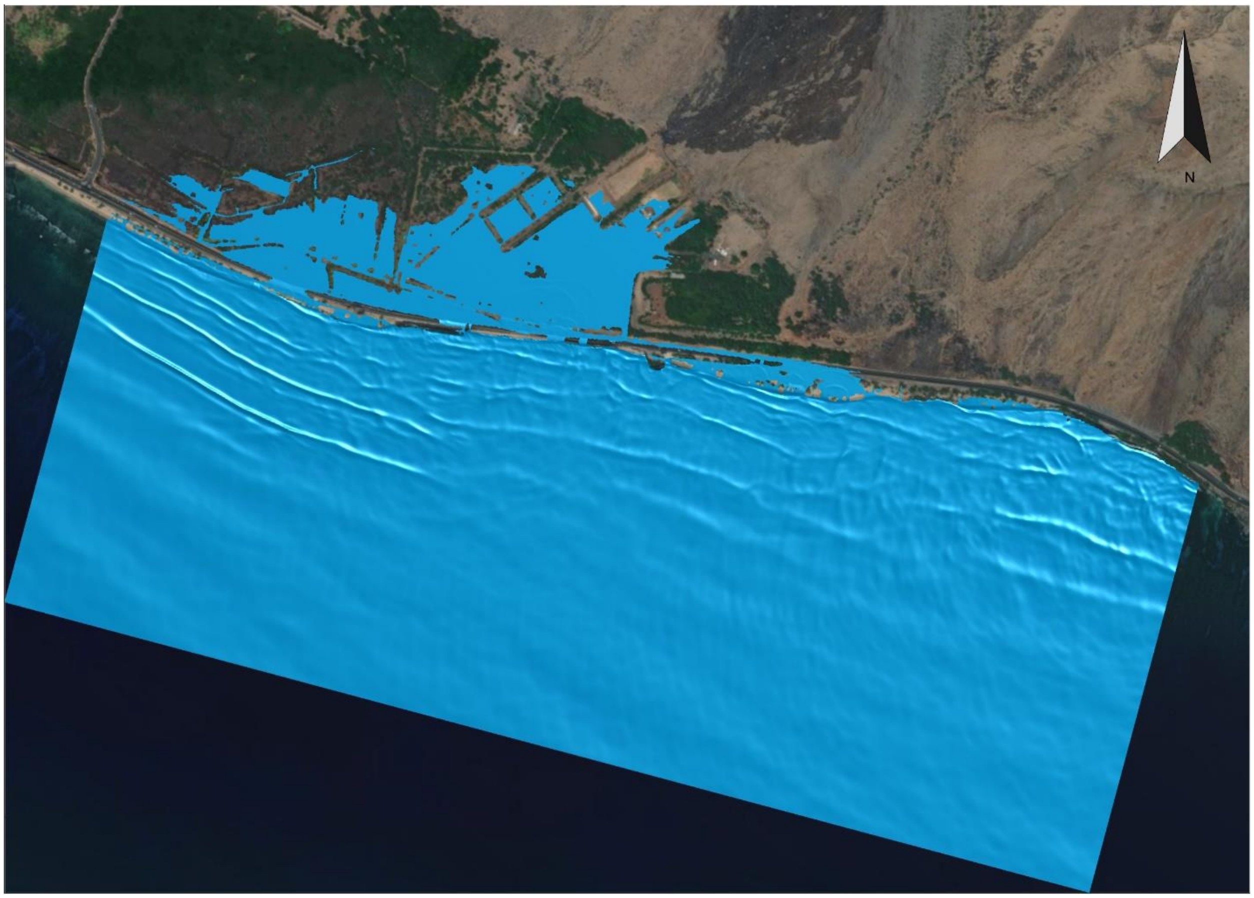

Figure 5-2. Region 1 XBeach-NH modeled water surface elevation snapshot for existing ground

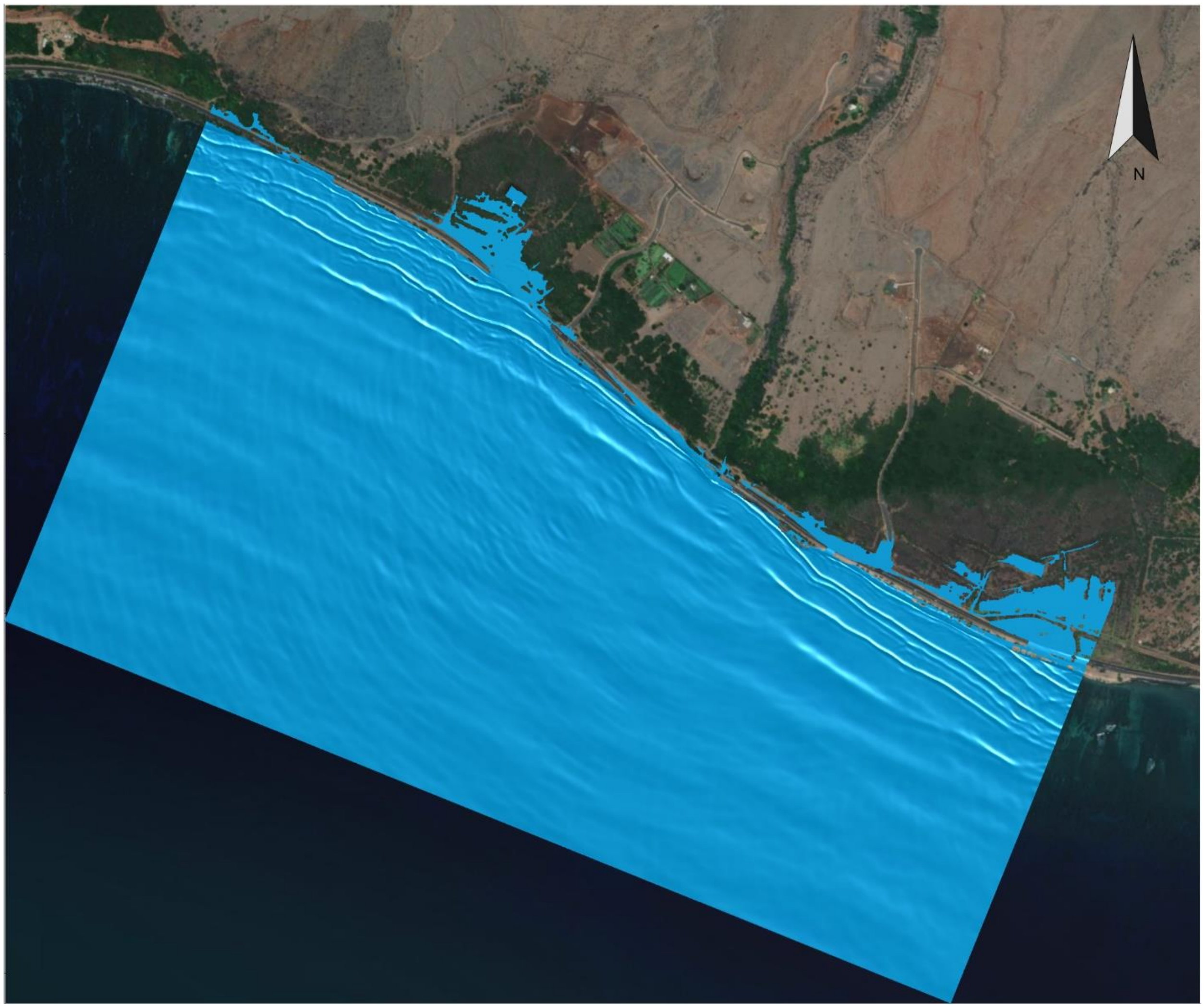

Figure 5-3. Region 2 XBeach-NH modeled water surface elevation snapshot for existing ground

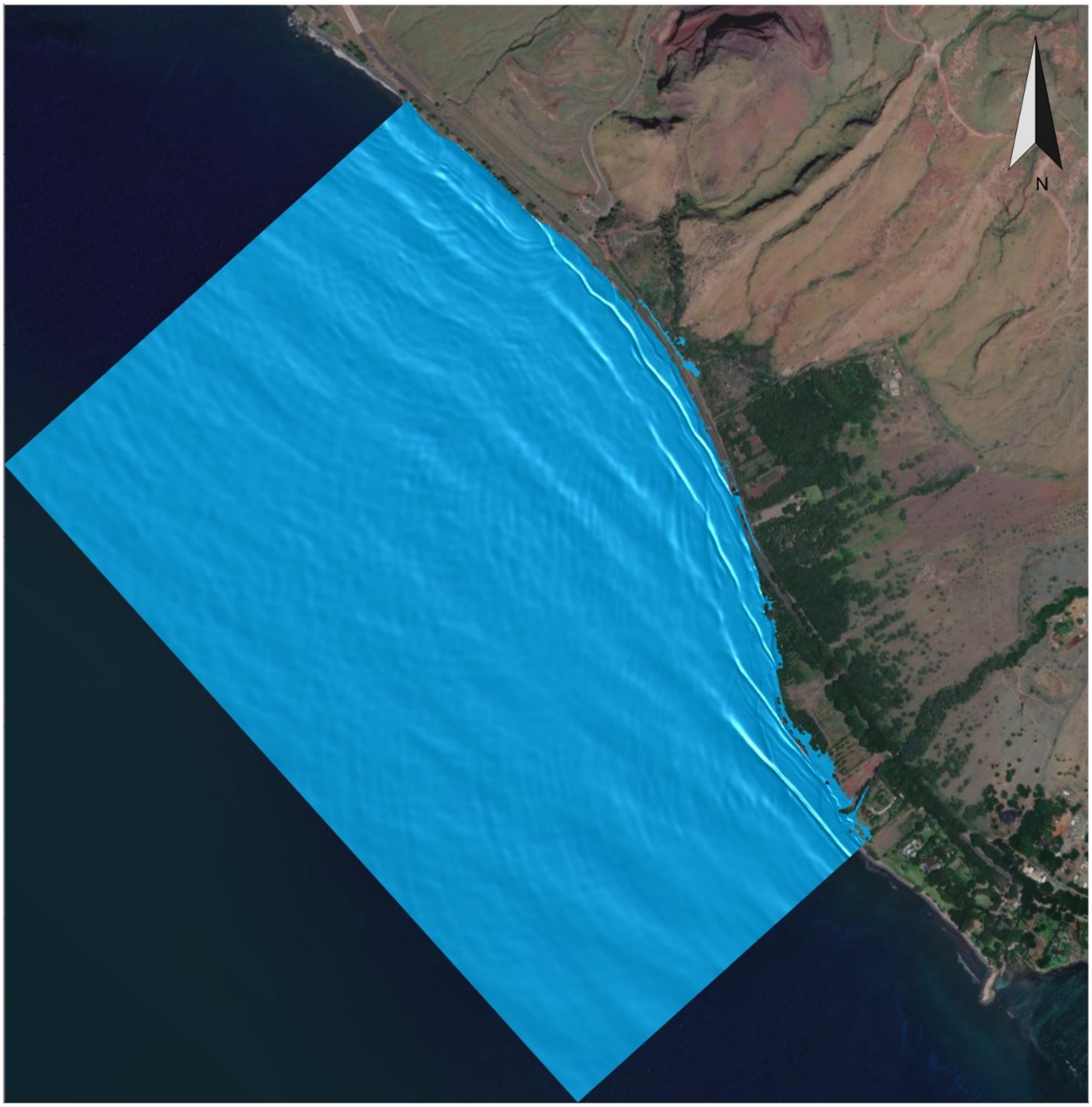

Figure 5-4. Region 3 XBeach-NH modeled water surface elevation snapshot for existing ground

5.2.1 *Existing Ground*

Existing flood extent and corresponding depths, elevations, and depth-averaged velocities are shown in Appendix A attached to this report. Figure 5-5 through Figure 5-12 shows the maximum flood extent for the modeled areas relative to the proposed alignment grading limits. Modeled existing ground flood extents and corresponding depths and elevations are summarized in Table 5-1, Table 5-2, Table 5-3, and Table 5-4 for alternative alignments 1, 2, 3, and 4, respectively.

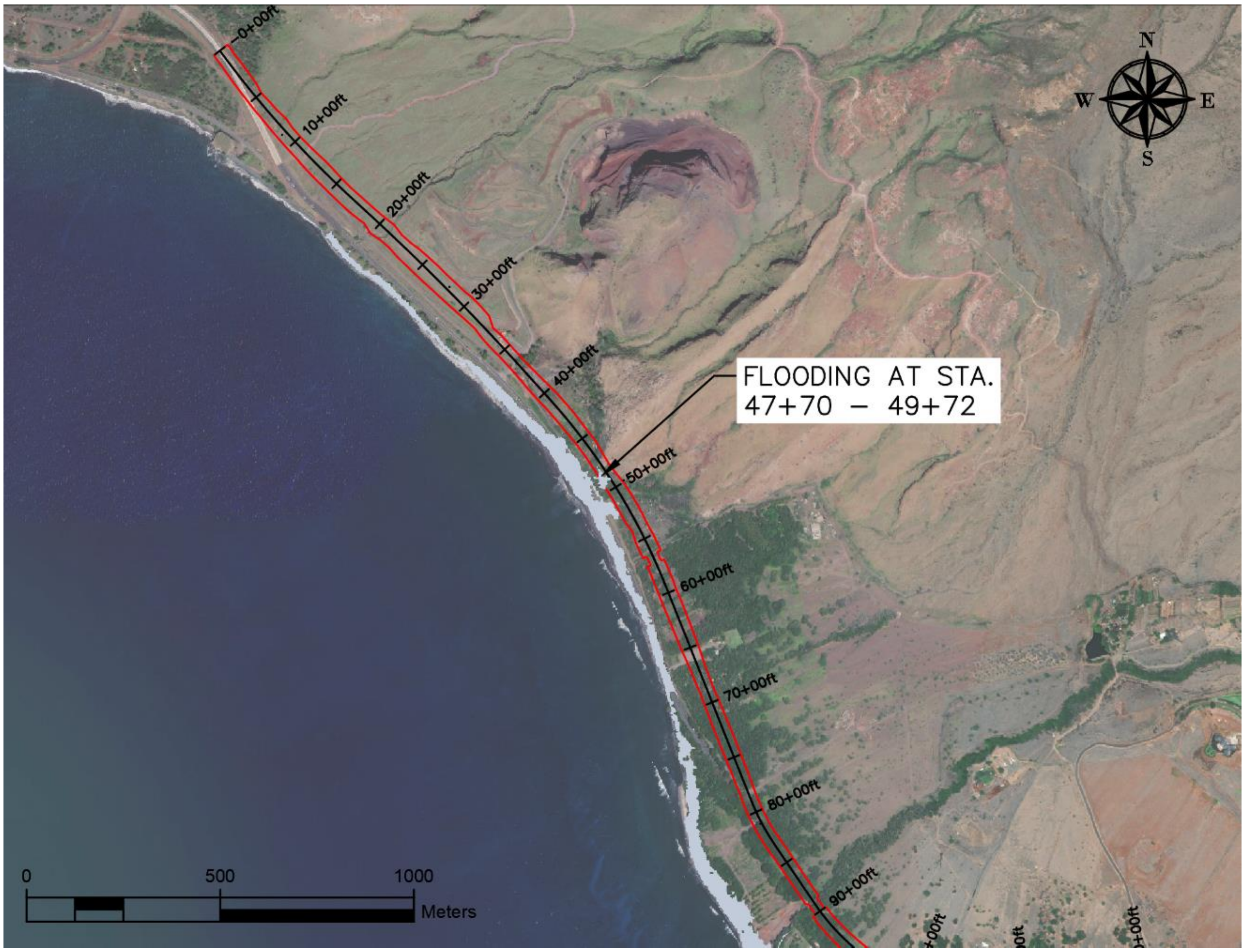

Figure 5-5. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 1 (red) alignment in the Olowalu region.

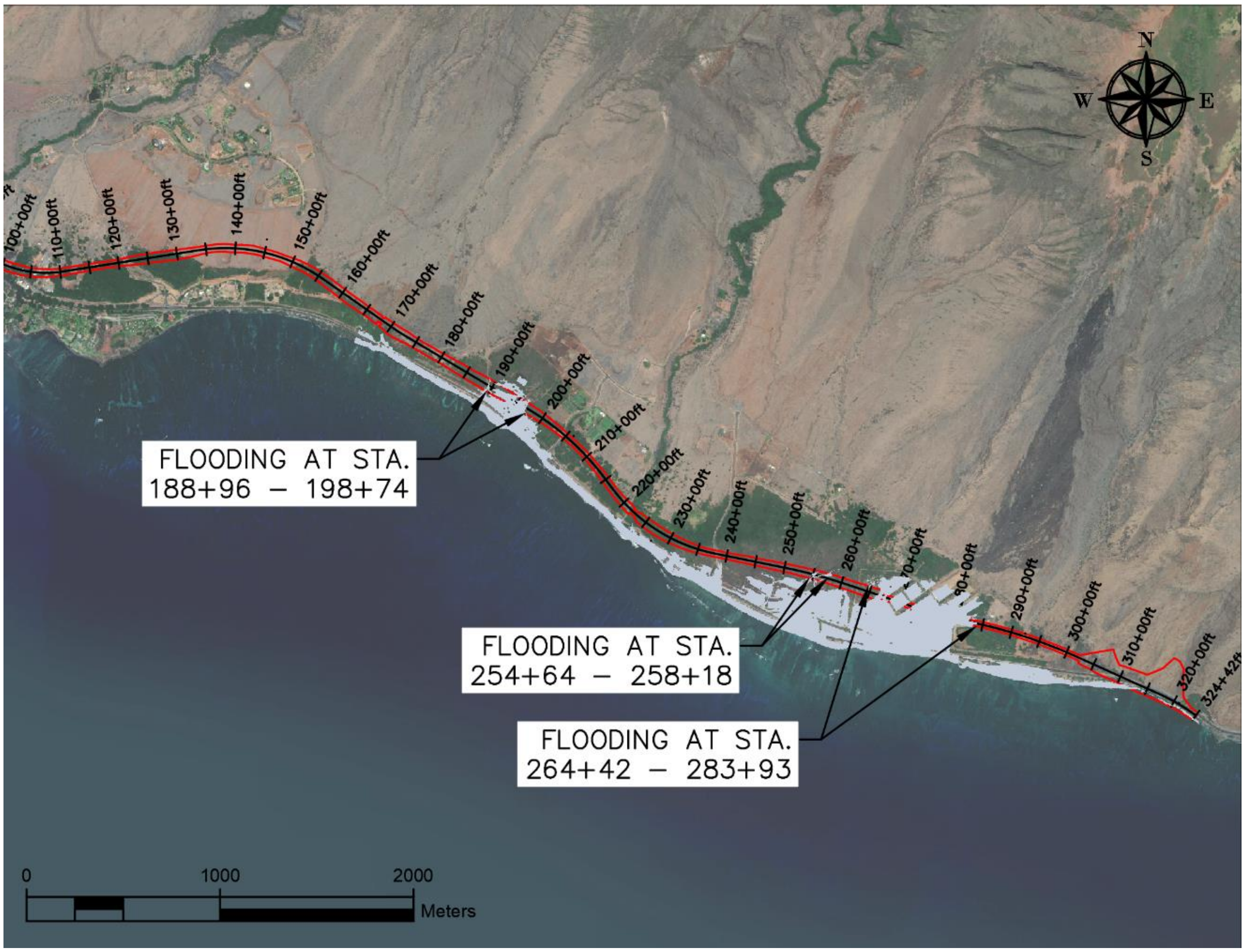

Figure 5-6. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 1 (red) alignment in the Ukumehame region.

Table 5-1. Modeled maximum flood depth and elevations for existing ground along the alternative 1 alignment

Alignment Station (ft)	Max Flood Depth (m [ft])	Max Flood Elevation (m [ft], msl)
47+70 – 49+72	0.31 (1.0)	2.04 (6.7)
188+96 – 198+74	1.42 (4.7)	2.15 (7.1)
254+64 – 258+18	0.66 (2.2)	1.55 (5.1)
264+42 – 283+93	1.00 (3.3)	1.79 (5.9)

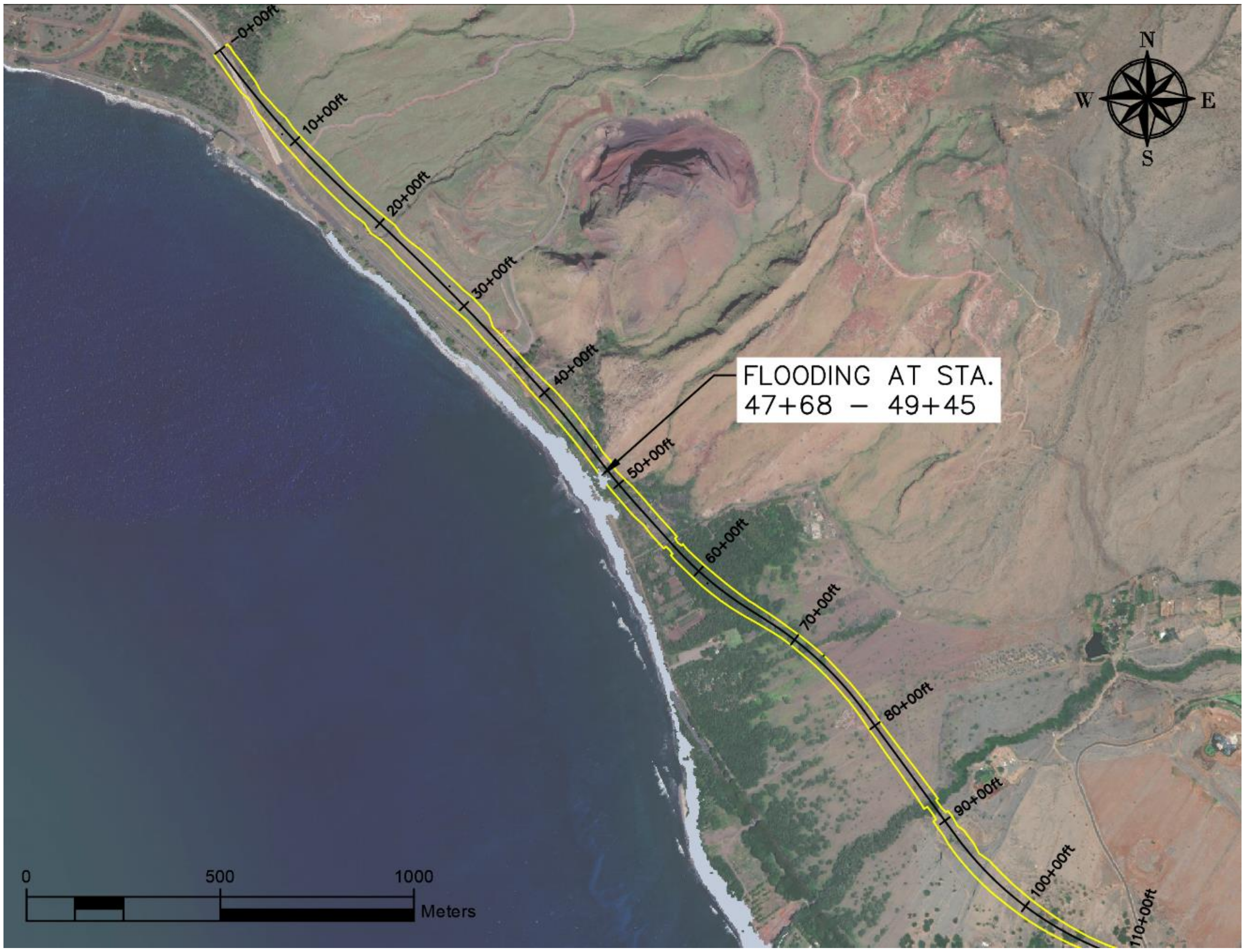

Figure 5-7. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 2 (yellow) alignment in the Olowalu region.

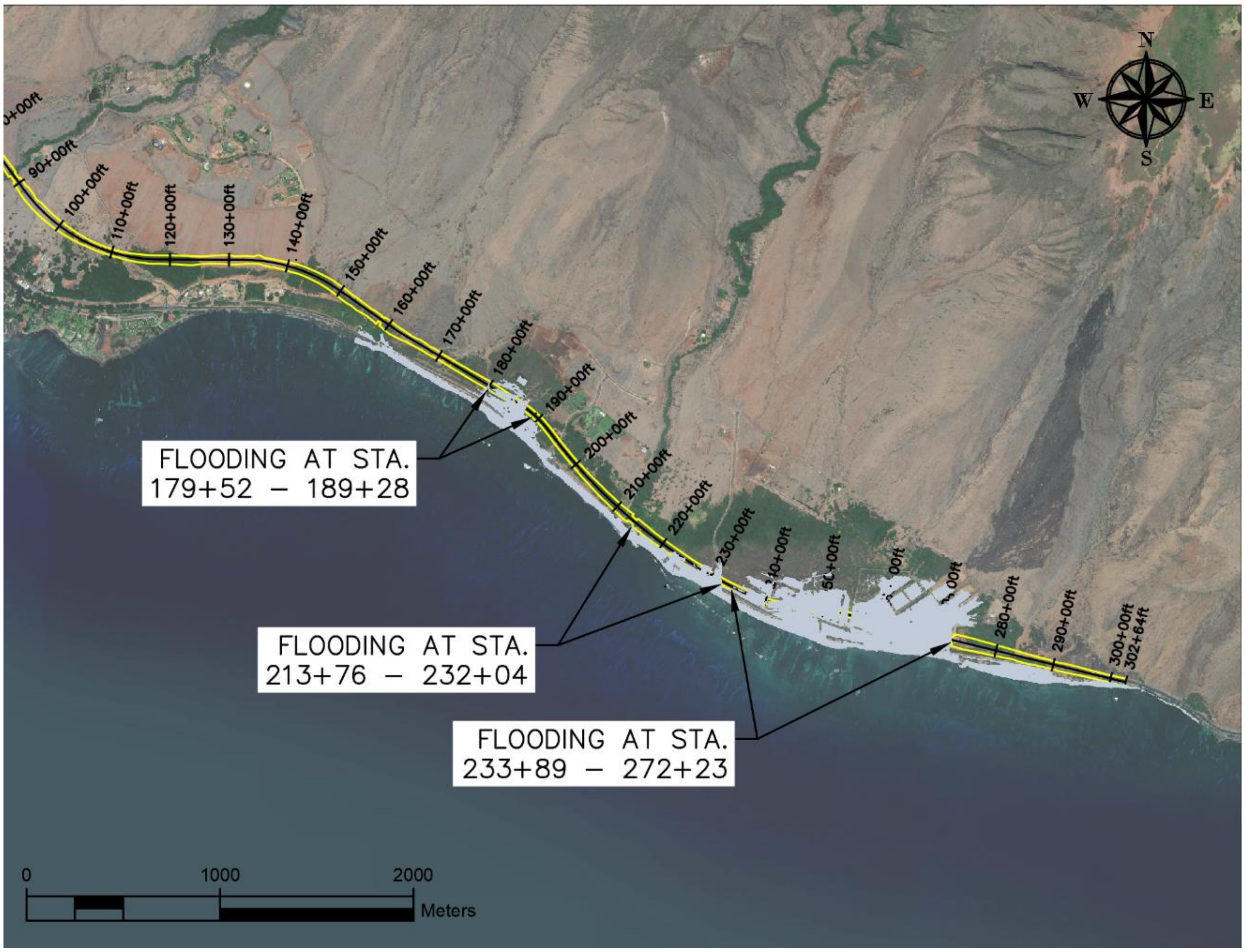

Figure 5-8. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 2 (yellow) alignment in the Ukumehame region.

Table 5-2. Modeled maximum flood depth and elevations for existing ground along the alternative 2 alignment

Alignment Station (ft)	Max Flood Depth (m [ft])	Max Flood Elevation (m [ft], msl)
47+68 – 49+45	0.25 (0.8)	2.04 (6.7)
179+52 – 189+28	1.42 (4.7)	2.15 (7.1)
213+76 – 232+04	1.03 (3.4)	2.01 (6.6)
233+89 – 272+23	1.16 (3.8)	1.82 (6.0)

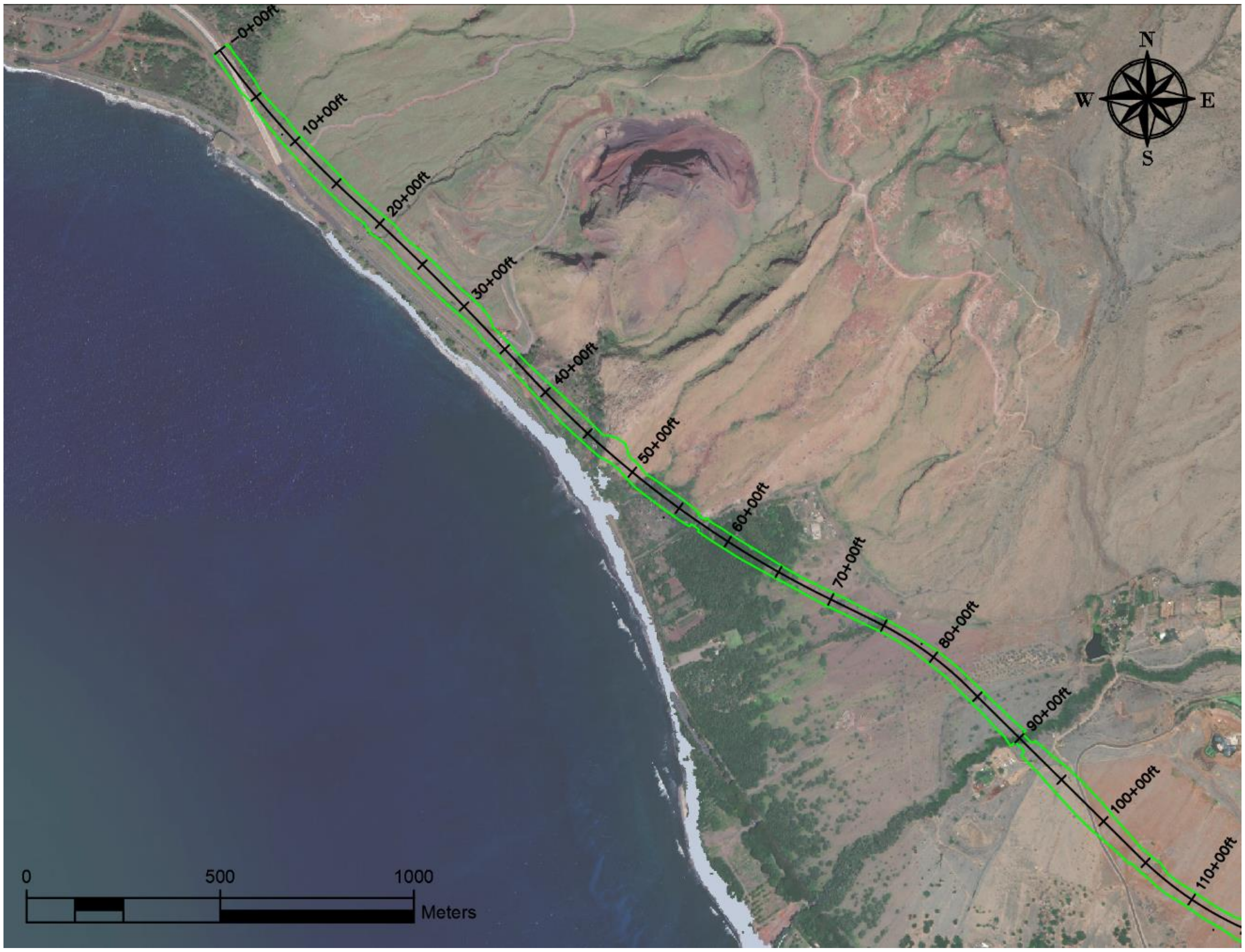

Figure 5-9. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 3 (geen) alignment in the Olowalu region.

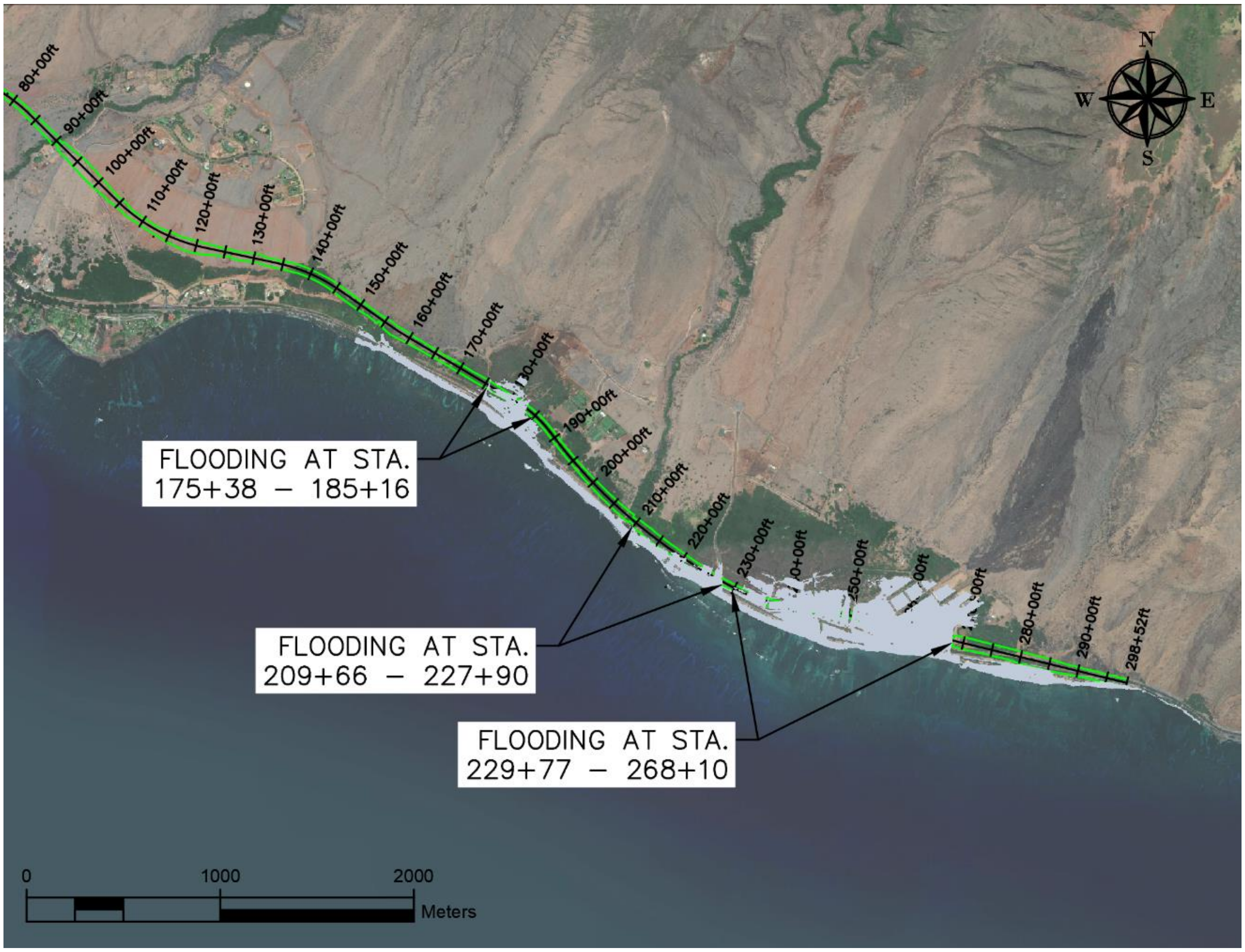

Figure 5-10. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 3 (geen) alignment in the Ukumehame region.

Table 5-3. Modeled maximum flood depth and elevations for existing ground along the alternative 3 alignment

Alignment Station (ft)	Max Flood Depth (m [ft])	Max Flood Elevation (m [ft], msl)
175+38 – 185+16	1.42 (4.7)	2.15 (7.1)
209+66 – 227+90	1.03 (3.4)	2.01 (6.9)
229+77 – 268+10	1.16 (3.8)	1.82 (6.0)

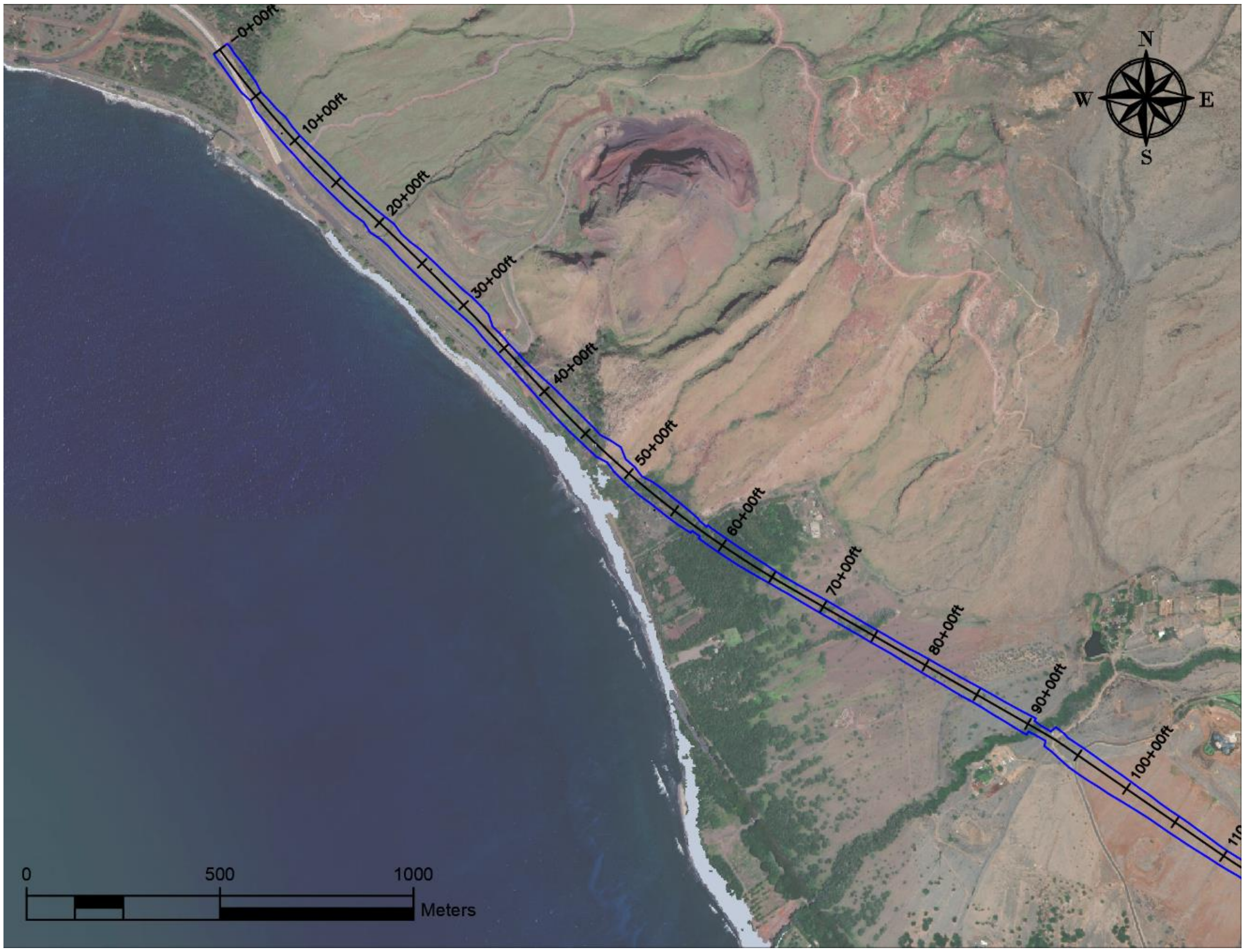

Figure 5-11. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 4 (blue) alignment in the Olowalu region.

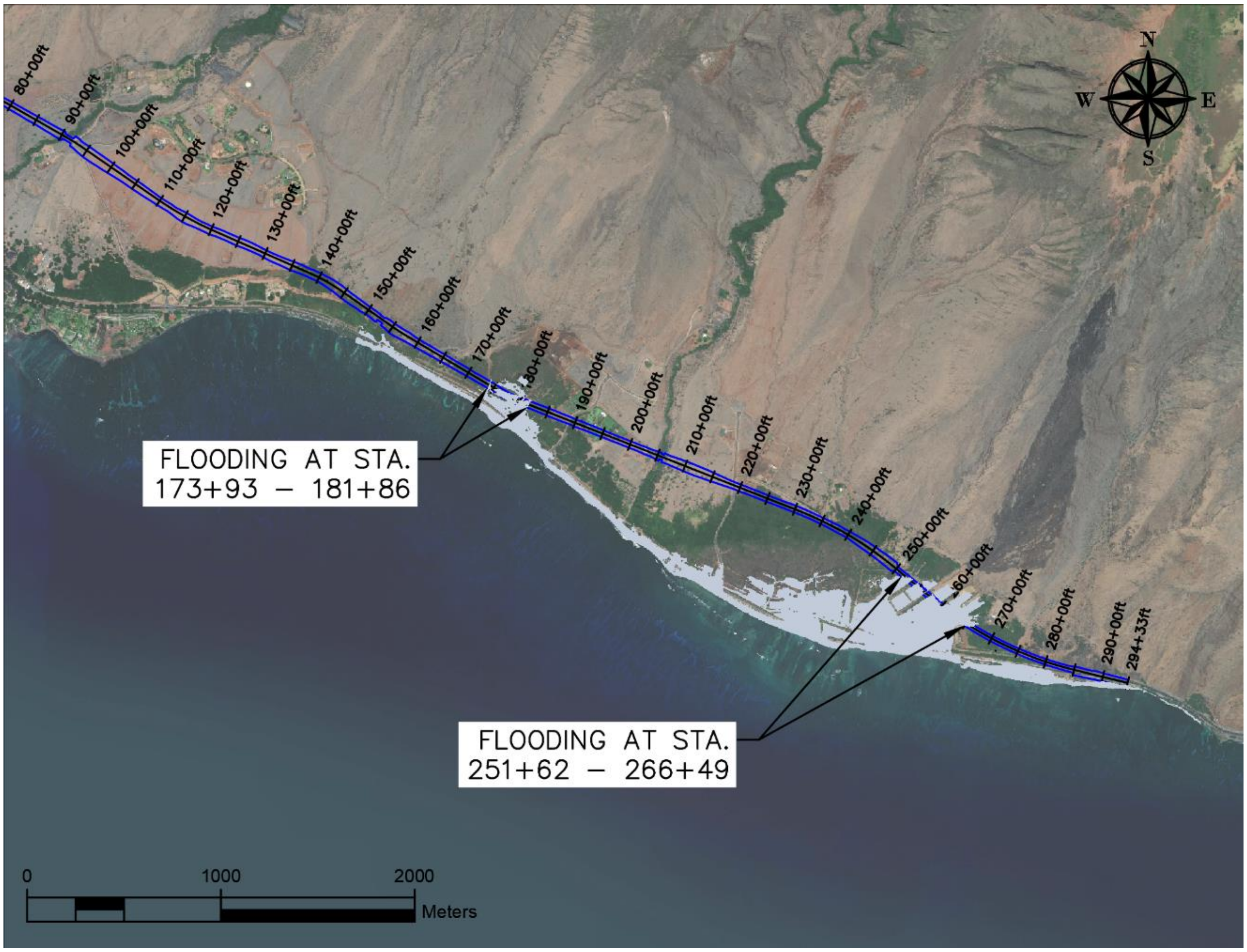

Figure 5-12. XBeach-NH modeled maximum flood extent (gray) for existing ground relative to alternative 4 (blue) alignment in the Ukumehame region.

Table 5-4. Modeled maximum flood depth and elevations for existing ground along the alternative 4 alignment

Alignment Station (ft)	Max Flood Depth (m [ft])	Max Flood Elevation (m [ft], msl)
173+93 – 181+86	0.77 (2.5)	2.06 (6.8)
251+62 – 266+49	0.92 (3.0)	1.78 (5.8)

5.2.2 *Alternative 1 Alignment*

Model results of maximum flood depths and elevations for the proposed alternative 1 alignment ground elevation changes are shown in Appendix B attached to this report. Figure 5-13 and Figure 5-14 show the maximum flood extent for the *Olowalu* and *Ukumehame* areas, respectively, relative to the proposed alignment grading limits.

Figure 5-13. *Olowalu* XBeach-NH modeled maximum flood extent (gray) for alternative 1 (red) alignment

Figure 5-14. *Ukumehame* XBeach-NH modeled maximum flood extent (gray) for alternative 1 (red) alignment

Olowalu

In the *Olowalu* region, the modeled flooding does not cross over the proposed grading limits. Due to the increase in elevation for this highway alignment, flood waters that previously crossed over the proposed grading limits under existing conditions are now blocked and limited to the makai edge of the proposed highway embankment. Modeled flooding reaches the makai edge of the proposed grading limits from stations 48+34 to 49+82 ft with maximum depth-averaged velocities up to 0.25 m/s (0.8 ft/s). This area may be susceptible to erosion without bank protection in the future under higher sea levels.

Ukumehame

In the *Ukumehame* region, the modeled flooding does not cross over the proposed alignment grading limits except for the proposed bridge crossing region between stations 267+00 and 284+00 ft where flood waters are assumed to pass freely below the bridge structure. The modeled maximum flood depth within the bridge crossing area is up to 1.00 m (3.3 ft) with a maximum surface elevation up to 1.79 m (5.9 ft) above msl. Due to the increase in grade for this highway alignment, flood waters that previously crossed over the proposed grading limits under existing conditions are now blocked and limited to the makai edge of the proposed highway embankment. Modeled flooding reaches the makai edge of the proposed grading limits from stations 189+00 to 198+50 ft, 254+59 to 256+50 ft, and 265+50 to 267+00 ft with maximum depth-averaged velocities between 1.09 m/s (3.6 ft/s) and 0.28 m/s (0.9 ft/s). These areas may be susceptible to erosion without bank protection in the future under higher sea levels.

5.2.3 *Alternative 2 Alignment*

Model results of maximum flood depths and elevations for the proposed alternative 2 alignment ground elevation changes are shown in Appendix C attached to this report. Figure 5-15 and Figure 5-16 show the maximum flood extent for the *Olowalu* and *Ukumehame* areas, respectively, relative to the proposed alignment grading limits.

Figure 5-15. *Olowalu* XBeach-NH modeled maximum flood extent (gray) for alternative 2 (yellow) alignment

Figure 5-16. *Ukumehame* XBeach-NH modeled maximum flood extent (gray) for alternative 2 (yellow) alignment

Olowalu

In the *Olowalu* region, the modeled flooding does not cross over the proposed alignment grading limits. Due to the increase in grade for this highway alignment, flood waters that previously crossed over the proposed grading limits under existing conditions are now blocked and limited to the makai edge of the proposed highway embankment. Modeled flooding reaches the makai edge of the proposed grading limits from stations 48+25 to 49+67 ft with maximum depth-averaged velocities up to 0.25 m/s (0.8 ft/s). This area may be susceptible to erosion without bank protection in the future under higher sea levels.

Ukumehame

In the *Ukumehame* region, the modeled flooding partially crosses over the proposed alignment grading limits between stations 185+89 and 187+37 ft with maximum flood depth up to 0.36 m (1.2 ft) and elevation up to 2.12 m (7.0 ft) above msl. Flooding also occurs between stations 229+91 and 233+52 ft with maximum flood depth up to 0.39 m (1.3 ft) and elevation up to 1.95 m (6.4 ft) above msl. This area is low-lying and intersects Pohaku Aeko Street. Due to the increase in grade for this highway alignment, flood waters that previously crossed over the proposed alignment under existing conditions, outside of the area described above, are now blocked and limited to the makai edge of the highway grading limits. Modeled flooding reaches the makai edge of the grading limits from stations 179+72 to 187+25 ft and 213+76 to 232+04 ft with maximum depth-averaged velocities up to 0.93 m/s (3.1 ft/s) and 1.20 m/s (3.9 ft/s), respectively. These areas may be susceptible to erosion without bank protection in the future under higher sea levels. Modeled flooding also extends past the proposed bridge crossing region between station 240+00 and 272+50 ft where flood waters are assumed to pass freely below the bridge structure. The modeled maximum flood depth within the bridge crossing area is up to 1.16 m (3.8 ft) with a maximum surface elevation up to 1.82 m (6.0 ft) above msl.

5.2.4 *Alternative 3 Alignment*

Model results of maximum flood depths and elevations for the proposed alternative 3 alignment ground elevation changes are shown in Appendix D attached to this report. Figure 5-17 and Figure 5-18 show the maximum flood extent for the *Olowalu* and *Ukumehame* areas, respectively, relative to the proposed alignments grading limits.

Figure 5-17. *Olowalu* XBeach-NH modeled maximum flood extent (gray) for alternative 3 (green) alignment

Figure 5-18. *Ukumehame* XBeach-NH modeled maximum flood extent (gray) for alternative 3 (green) alignment

Olowalu

In the *Olowalu* region, the modeled flooding does not cross over the proposed alignment grading limits or reach the makai embankment.

Ukumehame

In the *Ukumehame* region, the modeled flooding within the proposed alignment grading limits occurs between stations 181+01 and 183+20 ft with maximum flood depth up to 0.36 m (1.2 ft) and elevation up to 2.12 m (7.0 ft) above msl. Flooding also occurs between stations 225+97 and 229+41 ft with maximum flood depth up to 0.39 m (1.3 ft) and elevation up to 1.95 m (6.4 ft) above msl. This area is low-lying and intersects Pohaku Aeko Street. Due to the increase in grade for this highway alignment, flood waters that previously crossed over the proposed alignment under existing conditions, outside of the area described above, are now blocked and limited to the makai edge of the highway grading limits. Modeled flooding reaches the makai edge of the grading limits from stations 175+80 to 183+13 ft and 209+66 to 228+35 ft with maximum depth-averaged velocities up to 0.80 m/s (2.6 ft/s) and 1.40 m/s (4.6 ft/s), respectively. These areas may be susceptible to erosion without bank protection in the future under higher sea levels. Flooding also extends past the proposed bridge crossing region between station 239+00 and 268+00 ft where flood waters are assumed to pass freely below the bridge structure. The modeled maximum flood depth within the bridge crossing area is up to 1.16 m (3.8 ft) with a maximum surface elevation up to 1.82 m (6.0 ft) above msl.

5.2.5 *Alternative 4 Alignment*

Model results of maximum flood depths and elevations for the proposed alternative 4 alignment ground elevation changes are shown in Appendix E attached to this report. Figure 5-19 and Figure 5-20 show the maximum flood extent for the *Olowalu* and *Ukumehame* areas, respectively, relative to the proposed alignments grading limits.

Figure 5-19. *Olowalu* XBeach-NH modeled maximum flood extent (gray) for alternative 4 (blue) alignment

Figure 5-20. *Ukumehame* XBeach-NH modeled maximum flood extent (gray) for alternative 4 (blue) alignment

Olowalu

In the *Olowalu* region, the modeled flooding does not cross over the proposed alignment grading limits or reach the makai embankment.

Ukumehame

In the *Ukumehame* region, the modeled flooding does not occur within the proposed alignment grading limits except for the proposed bridge crossing region between station 251+62 and 266+49 ft where flood waters are assumed to pass freely below the bridge structure. The modeled maximum flood depth within the bridge crossing area is up to 0.92 m (3.0 ft) with a maximum surface elevation up to 1.78 m (5.8 ft) above msl. Due to the increase in grade for this highway alignment, flood waters that previously crossed over the proposed alignment under existing conditions are now blocked and limited to the makai edge of the highway grading limits. Modeled flooding reaches the makai edge of the grading limits from stations 174+16 to 181+61 ft with maximum depth-averaged velocities up to 0.71 m/s (2.3 ft/s). This area may be susceptible to erosion without bank protection in the future under higher sea levels.

5.3 Alternatives Assessment

Table 5-5 and Table 5-6 below summarizes the total length of each highway alternative that is potentially exposed to modeled annual wave flooding with 0.98 m (3.2 ft) of slr for the *Olowalu* and *Ukumehame* regions, respectively. Based on the model results for the *Olowalu* region, highway alignment alternatives 3 and 4 are the least susceptible to potential flooding for the annual wave event where neither of these highway alignments are impacted by the modeled flooding. Highway alignment alternative 1 was found to be the most susceptible to potential flooding in the *Olowalu* region for an annual wave event where 45 m (148 ft) of highway is impacted. Based on the model results for the *Ukumehame* region, highway alignment alternative 4 is the least susceptible to potential flooding for the annual wave event where only 227 m (745 ft) of highway is impacted. Highway alignment alternative 2 was found to be the most susceptible to potential flooding in the *Ukumehame* region for an annual wave event where 835 m (2,741 ft) of highway is impacted. The modeled flooding under the bridge crossing region in *Ukumehame* is not included in the length of highway impacted assuming the bridge structure is higher than the flood waters. However, bridge supporting elements (i.e. piles, abutments, etc.) may be exposed to flood hazards and would require engineered protection against potential scour and hydraulic loading.

Based on these modeling results, if fill is to be used instead of a bridge structure in the *Ukumehame* regions, the fill embankment may be exposed to wave-driven and passive flooding and would require bank protection through armoring or other engineered means. It should be noted that these results are representative of an annually occurring (1-year return period) south swell wave event. Flooding may be more severe for less frequent but larger wave events combined with higher sea levels.

Table 5-5. Comparison of alternative alignments based on model results - *Olowalu*

Highway Alignment	Stationing Impacted by Modeled Flooding	Length of Highway Impacted by Modeled Flooding
Alternative 1	48+34 - 49+82 ft	45 m (148 ft)
Alternative 2	48+25 - 49+67 ft	43 m (142 ft)
Alternative 3	N/A	0 m (0 ft)
Alternative 4	N/A	0 m (0 ft)

Table 5-6. Comparison of alternative alignments based on model results - *Ukumehame*

Highway Alignment	Stationing Impacted by Modeled Flooding	Length of Highway Impacted by Modeled Flooding
Alternative 1	189+00 - 198+50 ft 254+59 - 256+50 ft 265+50 - 267+00 ft	394 m (1,291 ft)
Alternative 2	179+72 - 187+37 ft 213+76 - 233+52 ft	835 m (2,741 ft)
Alternative 3	175+80 - 183+20 ft 209+66 - 229+41 ft	828 m (2,715 ft)
Alternative 4	174+16 - 181+61 ft	227 m (745 ft)

6. FEMA FIRM FLOOD ZONES

The FEMA FIRM flood zones along the study area include Zones VE, AE, A, and AO. Zone VE represents the coastal high hazard zone and is defined by the inundation caused by a 1-percent annual chance tsunami or hurricane storm surge, whichever is greater. For tsunami dominated regions, Zone VE is defined where tsunami flood depths are 1.22m (4 ft) or deeper. For hurricane storm surge dominated regions, Zone VE is defined where wave heights are 0.91 m (3 ft) or higher. Zone AE within the coastal high hazard zone is defined where the tsunami flood depth is less than 1.22m (4 ft) or where the wave height is less than 0.91 m (3 ft) for hurricane storm surge. The flood zones within the coastal hazard zone were defined for existing topography and sea level and do not include future slr. Figure 6-1 shows the FEMA flood zones in relation to the proposed alignments along the study area.

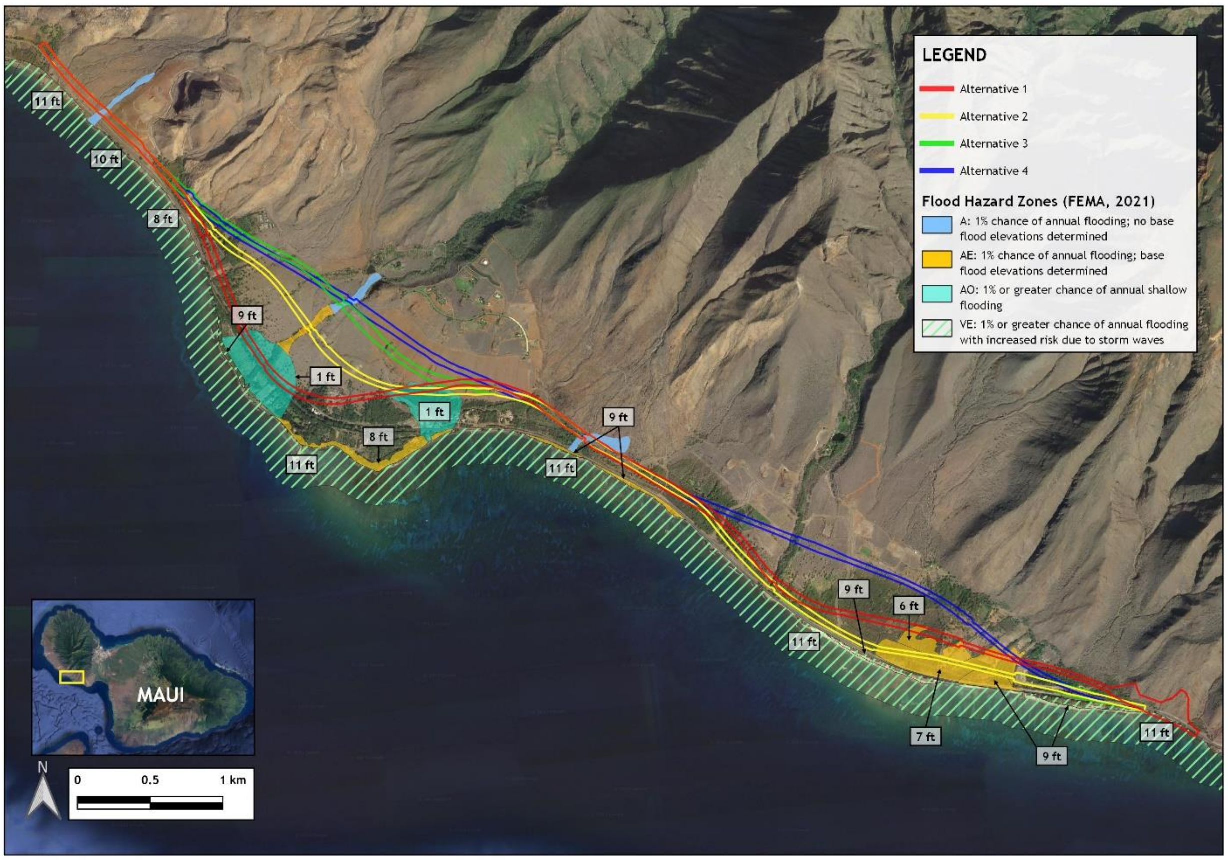

Figure 6-1. FEMA FIRM flood zones relative to the alternative alignments

All alternative alignments cross over the AE Zone at the southeast end of the study area. This area has a base flood elevation (BFE) between 1.82 m (6 ft) and 2.74 m (9 ft) above msl. The BFE of the VE Zones along the study area is between 2.44 m (8 ft) and 3.35 m (11 ft) above msl but do not cross over the proposed alignments.

7. COASTAL HIGHWAY INFRASTRUCUTRE ADAPTATION STRATEGIES

Highway infrastructure in the coastal zone may require special adaptation strategies when potentially exposed to coastal hazards along with future sea level rise. The Federal Highways report titled "*Highways in the Coastal Environment*" Report No. FHWA HIF-19-059 provides five (5) general strategies for highway infrastructure adaptation in the coastal regions. These general strategies include manage and maintain; increase redundancy; protect; accommodate; and relocate. Strategy appropriateness for this project shall be assessed by highway designers considering the varying physical environment along each alternative alignment and relative vicinity of coastal hazards with sea level rise. The following subsections describe each general strategy.

7.1 Manage and Maintain

Manage and maintain involves maintenance of existing highway infrastructure (i.e. sand sweeping, culvert cleaning, etc.) after high wave and water level events and managing the response to these extreme events through preparation (i.e. staging of road construction materials for highway repair). With future sea level rise the frequency of highway maintenance, storm response, and associated highway closure is expected to increase for this adaptation strategy. Depending on the highway elevation, vicinity to the shoreline, and future sea level rise projection, this strategy may become unviable if the coastal hazard impacts to highway infrastructure becomes too frequent.

7.2 Increase Redundancy

Increase redundancy involves providing other means of transportation (i.e. alternative routes or modes of transportation) during closure of the primary road or highway due to storm events. This strategy may become difficult or unviable in regions where alternative roads/highways or other means of transportation are not already in place and would require new infrastructure. If new routes are added away from the coastal hazards, this strategy would allow the existing route to remain open until no longer feasible due to future sea level rise projections.

7.3 Protect

Protect involves protecting existing or new highway infrastructure by a physical barrier to damaging coastal hazards. These barriers may consist of seawalls, revetments, and/or bulkheads. Rubble-mound revetments are a common and effective means to protect roads and/or highways that are exposed to wave action, flooding, and coastal erosion. These structures consist of an engineered slope made up of specifically sized stone or concrete armor unit based on a design wave height (typically 50-yr return period) at the toe of the structure. The crest elevation of a revetment can reduce wave overtopping during extreme events and the structure stability prohibits shoreline erosion and migration inland.

7.4 Accommodate

Accommodate involves highway infrastructure to be modified or re-designed to minimize impacts and to coexist with the future natural environment. An example of this strategy is raising a roadway or highway vertically above potential coastal hazards using an elevated structure (i.e. bridge, causeway, viaduct, etc.). This type of structure typically has a much smaller footprint than a raised highway built on top of fill material. The supporting elements of the elevated structure (i.e. piles, abutments, etc.) may still be exposed to coastal hazards and should be protected/designed accordingly.

7.5 Relocate

Relocate involves lessening or eliminating the exposure of coastal hazards by relocating the highway away from the shoreline and outside of any potential coastal hazards and future sea level rise. This strategy becomes difficult in narrow regions between the shoreline and steep topographic features, in regions that are low-lying and susceptible to future passive flooding, or in regions that are highly developed with little available land.

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Appendix A:

Global Sea Level Rise Projections

IPCC AR6 - Global Sea Level Rise Projections

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations (U.N.) body for assessing the science related to climate change. The IPCC was created to provide policymakers with periodic scientific assessments on climate change, its implications, and potential future risks. As part of this effort, the IPCC surveys and distills the existing body of scientific research and provides consensus projections on future sea levels across the globe under a range of possible future scenarios. The most recent iteration of the IPCC's work, the 6th Assessment Report (AR6), was published on August 9, 2021. Five Shared Socioeconomic Pathways (SSPs) representing future scenarios are described (Figure 1) with slr projections for each (Figure 2).

SSP1-1.9 Holds warming in 2100 to approximately 1.5°C relative to the years 1850 to 1900 after a slight overshoot (median) and implies net zero CO_2 emissions around the middle of the century.

SSP1-2.6 Stays below 2.0°C warming relative to the years 1850 to 1900 (median) with implied net zero emissions in the second half of the century.

SSP2-4.5 Approximately in line with the upper end of aggregate Nationally Determined Contribution (NDC) emission levels by 2030. SR1.5 assessed temperature projections for NDCs to be between 2.7 and 3.4°C by 2100, corresponding to the upper half of projected warming under SSP2-4.5. New or updated NDCs by the end of 2020 did not significantly change the emissions projections up to 2030, although more countries adopted 2050 net zero targets in line with SSP1-1.9 or SSP1-2.6. The SSP2-4.5 scenario deviates mildly from a "no-additional-climate-policy" reference scenario, resulting in best-estimate warming of around 2.7°C by the end of the 21st century relative to the years 1850 to 1900.

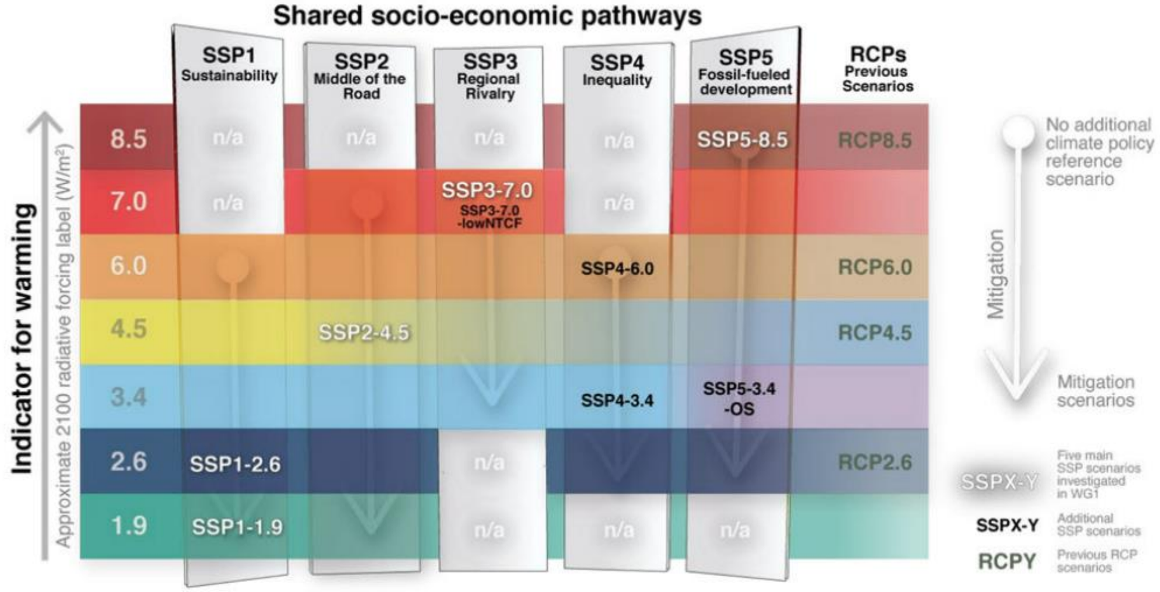
SSP3-7.0 A medium to high reference scenario resulting from no additional climate policy under the SSP3 socio-economic development narrative. SSP3-7.0 has particularly high non-CO_2 emissions, including high aerosol emissions.

SSP5-8.5 A high reference scenario with no additional climate policy. Emission levels as high as SSP5-8.5 are not obtained by Integrated Assessment Models under any of the SSPs other than the fossil-fueled SSP5 socio-economic development pathway.

To visualize the AR6 slr projections globally, NASA created the IPCC AR6 Sea Level Projection Tool [1], which allows users to view both global and regional sea level projections from 2020 to

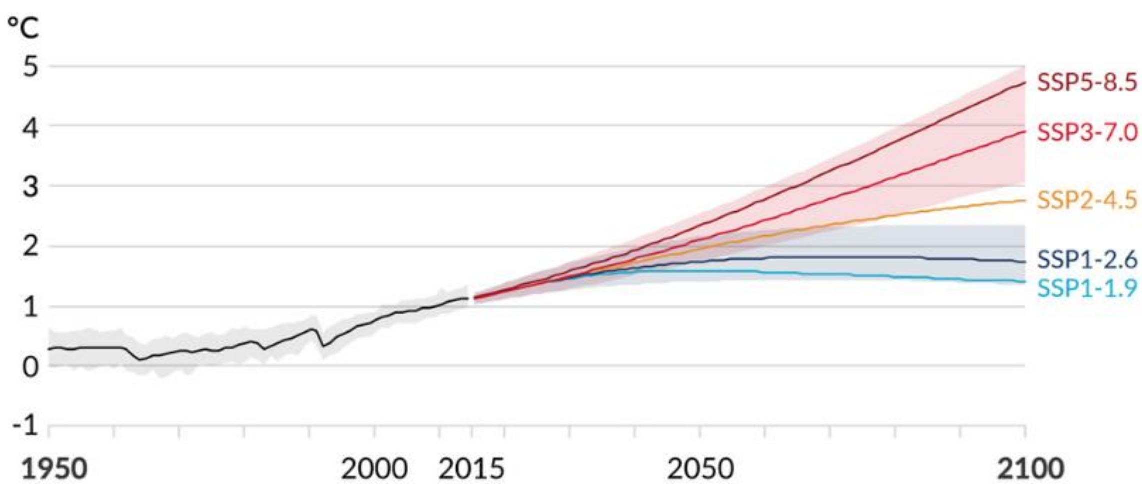
[1] https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool

2150 (Figure 3), along with how these projections differ depending on future scenarios. Users can click on a point anywhere in the ocean to obtain the IPCC projection of sea level for that specific location. The contributions of different physical processes to future slr are also provided, indicating which processes will be the dominant drivers of future sea levels for a given location.



The SSP scenarios used in this report, their indicative temperature evolution and radiative forcing categorisation, and the five socio-economic storylines upon which they are built. Source: IPCC (2021) Cross-Chapter Box 1.4, Figure 1.

Figure 1. IPCC AR6 shared socio-economic pathways (IPCC, 2021)



Global surface temperature changes relative to 1850-1900, degrees C, under the five core emissions scenarios used in AR6. Source: IPCC (2021) Figure SPM.8a.

Figure 2. IPCC AR6 global sea level rise projections, 1950 to 2100 (IPCC, 2021)

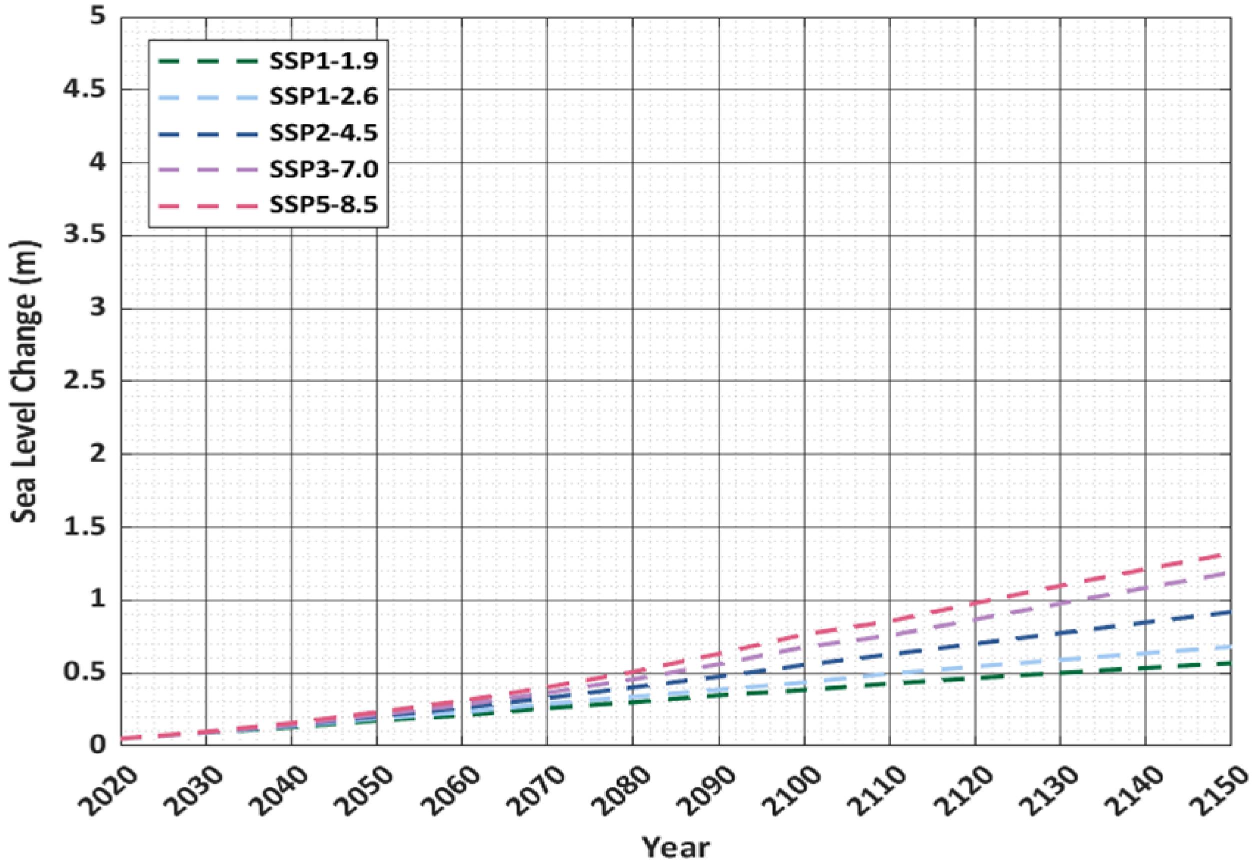


Figure 3. IPCC AR6 global sea level rise projections, 2020 to 2150 (IPCC, 2021)

U.S. Interagency Task Force - Global Sea Level Rise Projections

The Sea Level Rise and Coastal Flood Hazard Scenarios and Tools Interagency Task Force (Task Force) recently revised their sea level change projections through 2150, considering up-to-date scientific research and measurements. The Task Force consists of representatives from the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), U.S. Environmental Protection Agency (EPA), U.S. Geological Survey (USGS), U.S. Army Corps of Engineer (USACE), and additional partners within academia. The most recent report entitled *Global and Regional Sea Level Rise Scenarios for the United States: Updated Mean Projections and Extreme Water Level Probabilities Along U.S. Coastlines* (Sweet, et al., 2022), provides the most up to date slr projections for all the U.S. states and territories.

To visualize the Task Force slr projections globally, NASA created the *Task Force Sea Level Projection Tool* [2], which allows users to view both global and regional sea level projections from 2020 to 2150 (Figure 4), along with how these projections differ depending on future scenarios. Users can select a point anywhere in the ocean to obtain the Task Force slr projections for that

[2] https://sealevel.nasa.gov/task-force-scenario-tool

specific location. The contributions of different physical processes to future slr are also provided, indicating which processes will be the dominant drivers of future sea levels for a given location.

The Task Force scenarios are different than the IPCC AR6 scenarios but are based on the same underlying science and slr projection framework as the IPCC efforts. The key difference is that the Task Force created scenarios for targeted slr elevations at specific times in the future, rather than emissions pathways. These targeted slr elevations represent unlikely but possible, or plausible, outcomes compared to IPCC AR6, which are considered likely scenarios. The goal of the Task Force projections is to examine the full range of plausible amounts of future sea level to help bound certain risk planning exercises. The result for the Task Force is that the scenarios are based on target elevations for slr in 2100 of 0.30 m (1.0 ft) (*Low*), 0.49 m (1.6 ft) (*Intermediate Low*), 1.01 m (3.3 ft) (*Intermediate*), 1.49 m (4.9 ft) (*Intermediate High*), and 2.01 m (6.6 ft) (*High*). Comparisons of the global Task Force slr projections to IPCC AR6 global projections are shown in Figure 5.

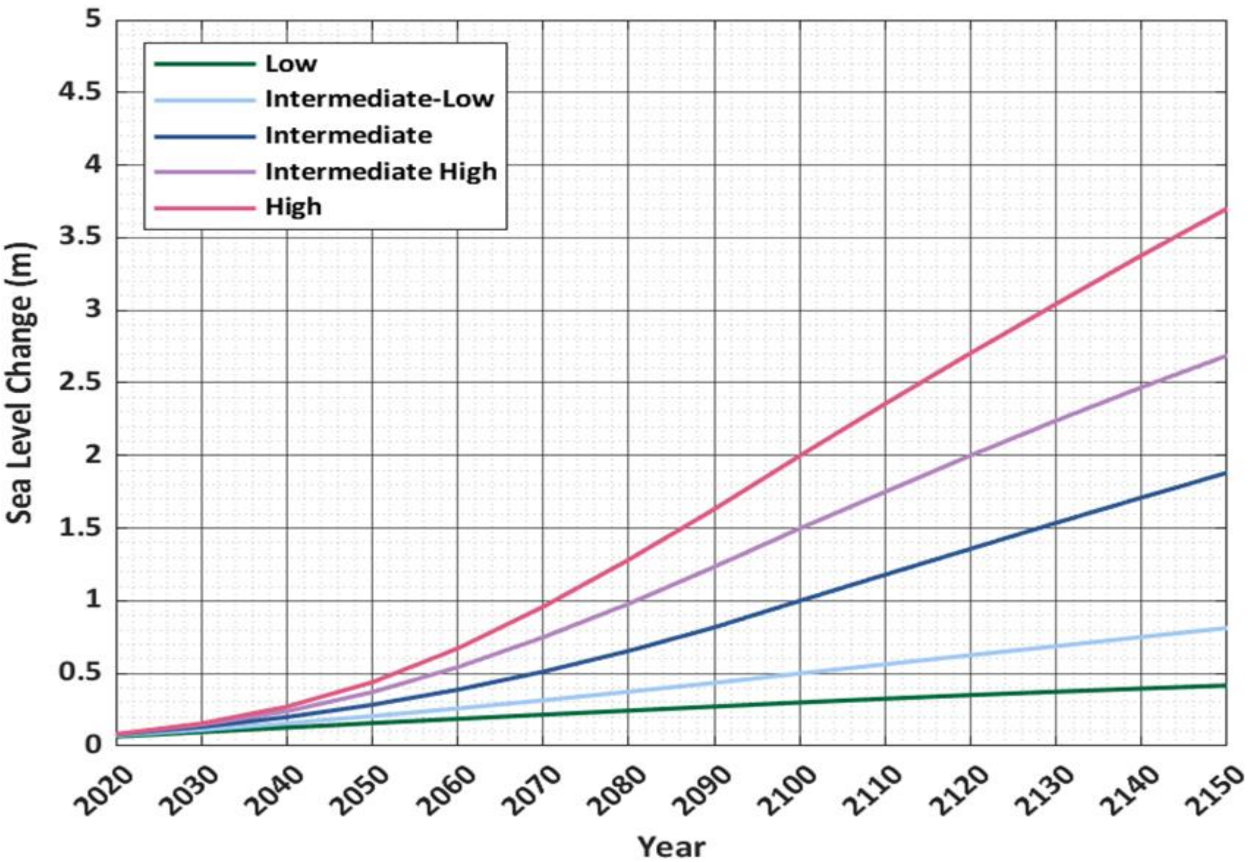


Figure 4. Task Force global sea level rise projections, 2020 to 2150 (Sweet, et al., 2022)

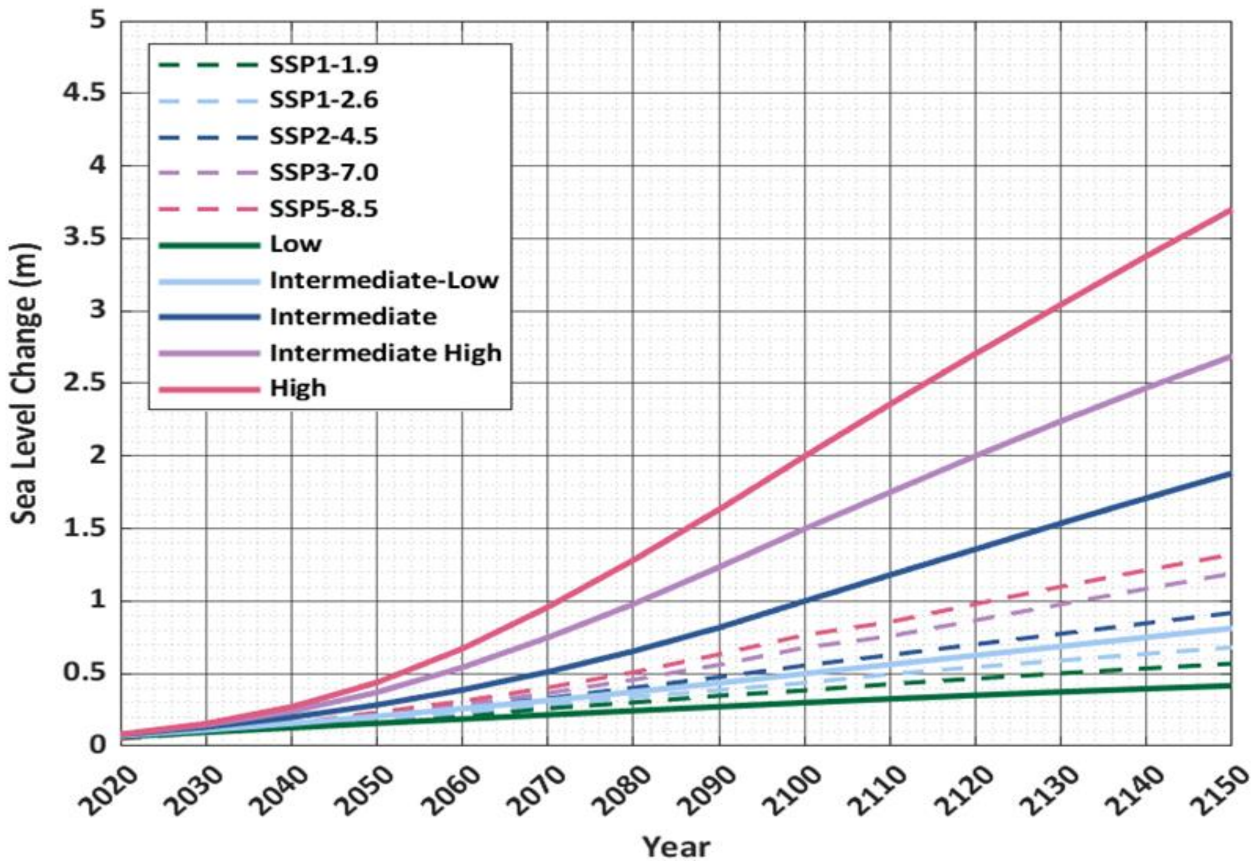


Figure 5. Comparison of IPCC AR6 and Task Force global sea level rise projections

Appendix B:

XBEACH-NH MODELED FLOOD DEPTHS, ELEVATIONS, AND VELOCITIES – EXISTING TOPOGRAPHY

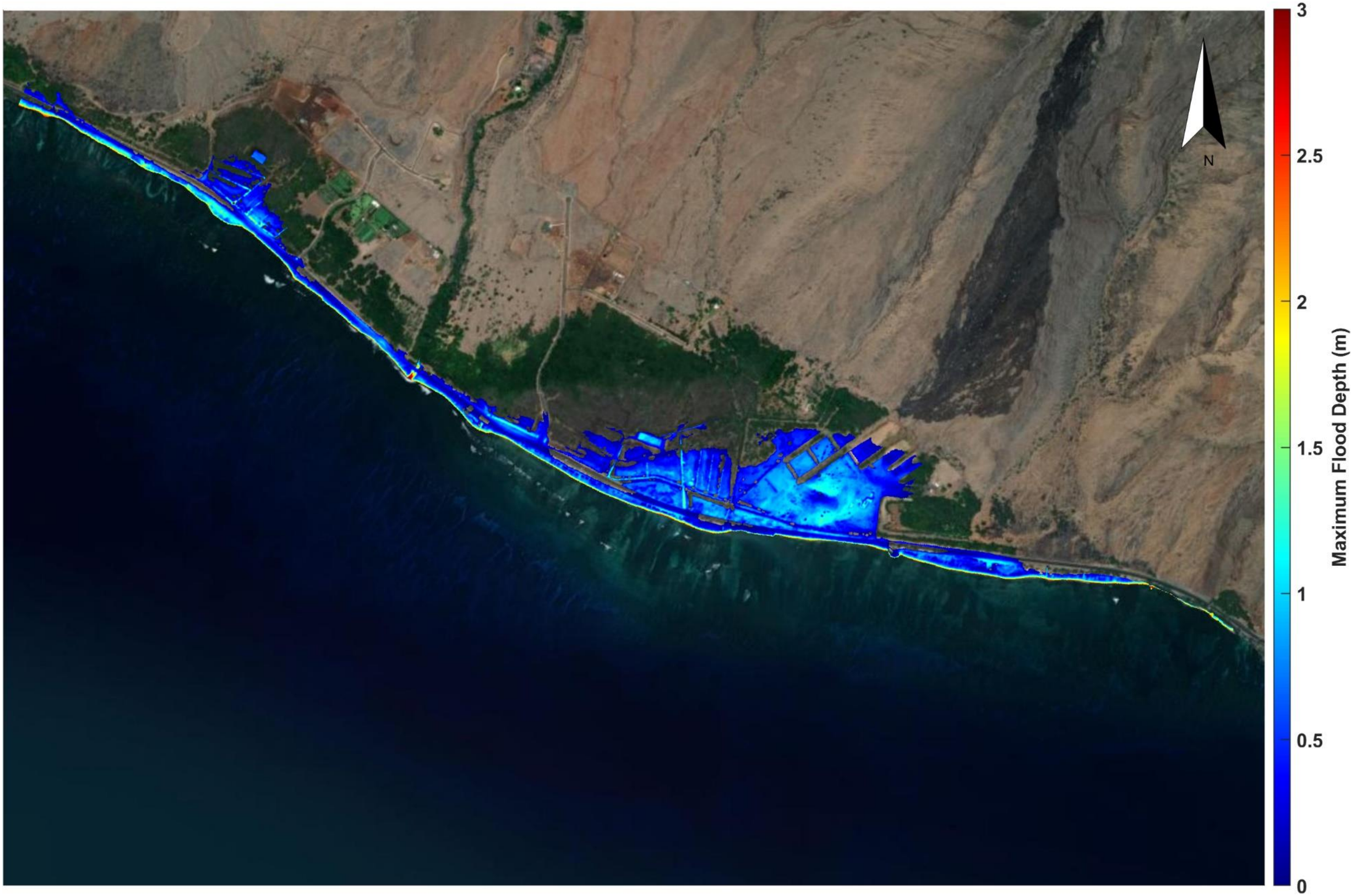


Figure B-1. XBeach-NH modeled maximum flood depth for existing ground (Ukumehame)

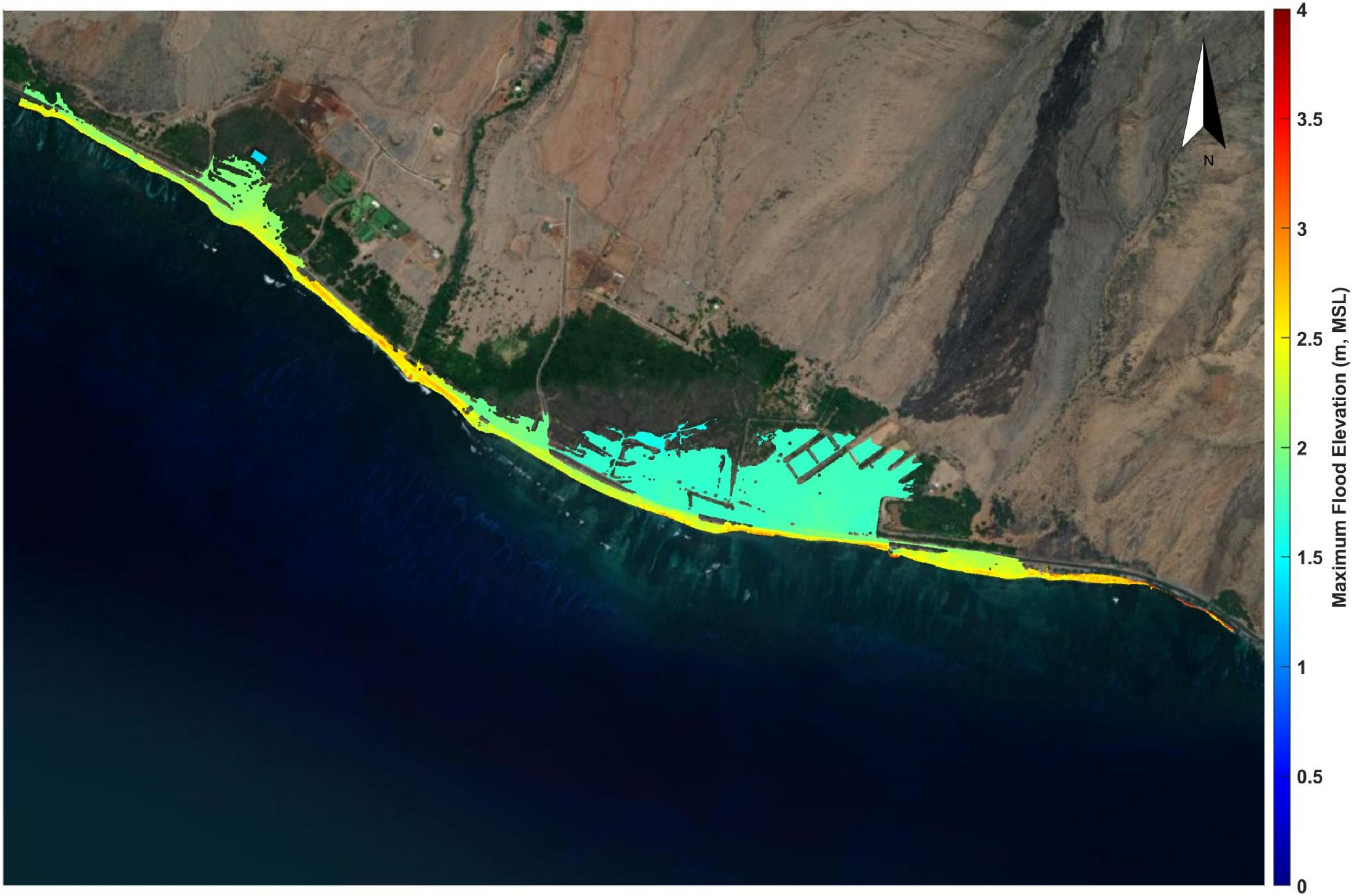


Figure B-2. XBeach-NH modeled maximum flood elevation for existing ground (Ukumehame)

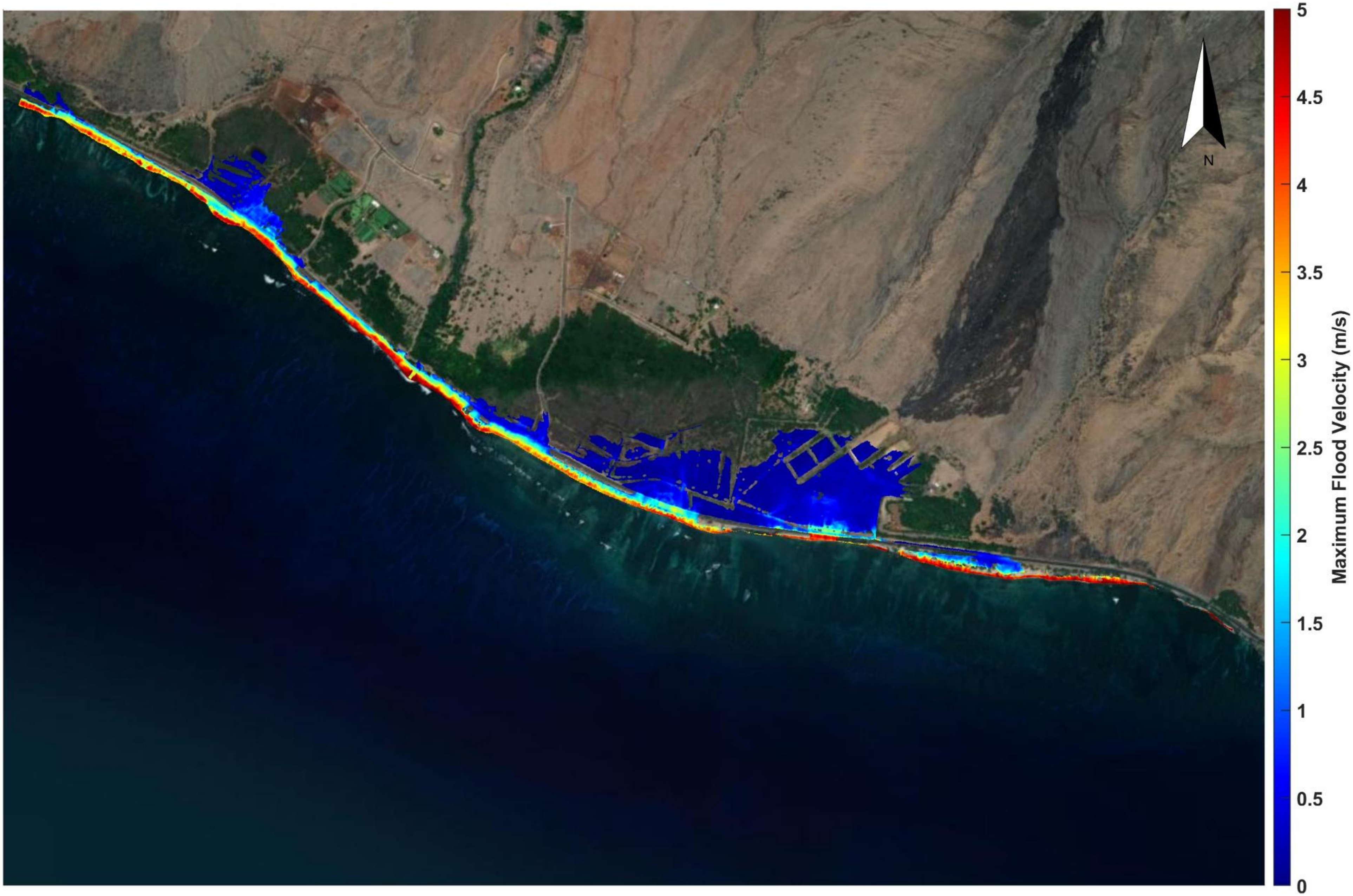


Figure B-3. XBeach-NH modeled maximum flood depth-averaged velocity for existing ground (Ukumehame)

Figure B-4. XBeach-NH modeled maximum flood depth for existing ground (Olowalu)

Figure B-5. XBeach-NH modeled maximum flood elevation for existing ground (Olowalu)

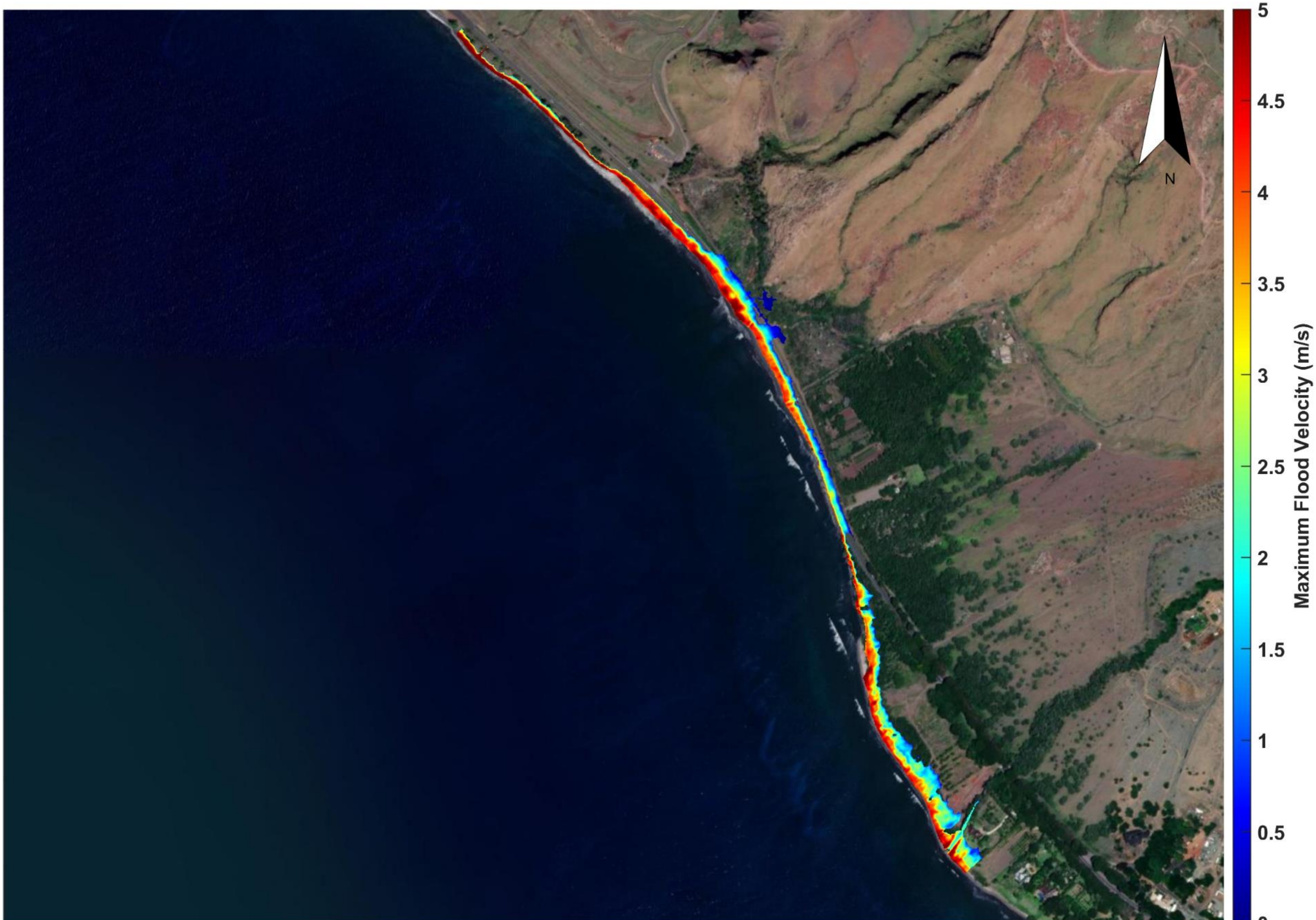


Figure B-6. XBeach-NH modeled maximum flood depth-averaged velocity for existing ground (Olowalu)

Appendix C:

XBEACH-NH MODELED FLOOD DEPTHS, ELEVATIONS, AND VELOCITIES – ALTERNATIVE 1 ALIGNMENT

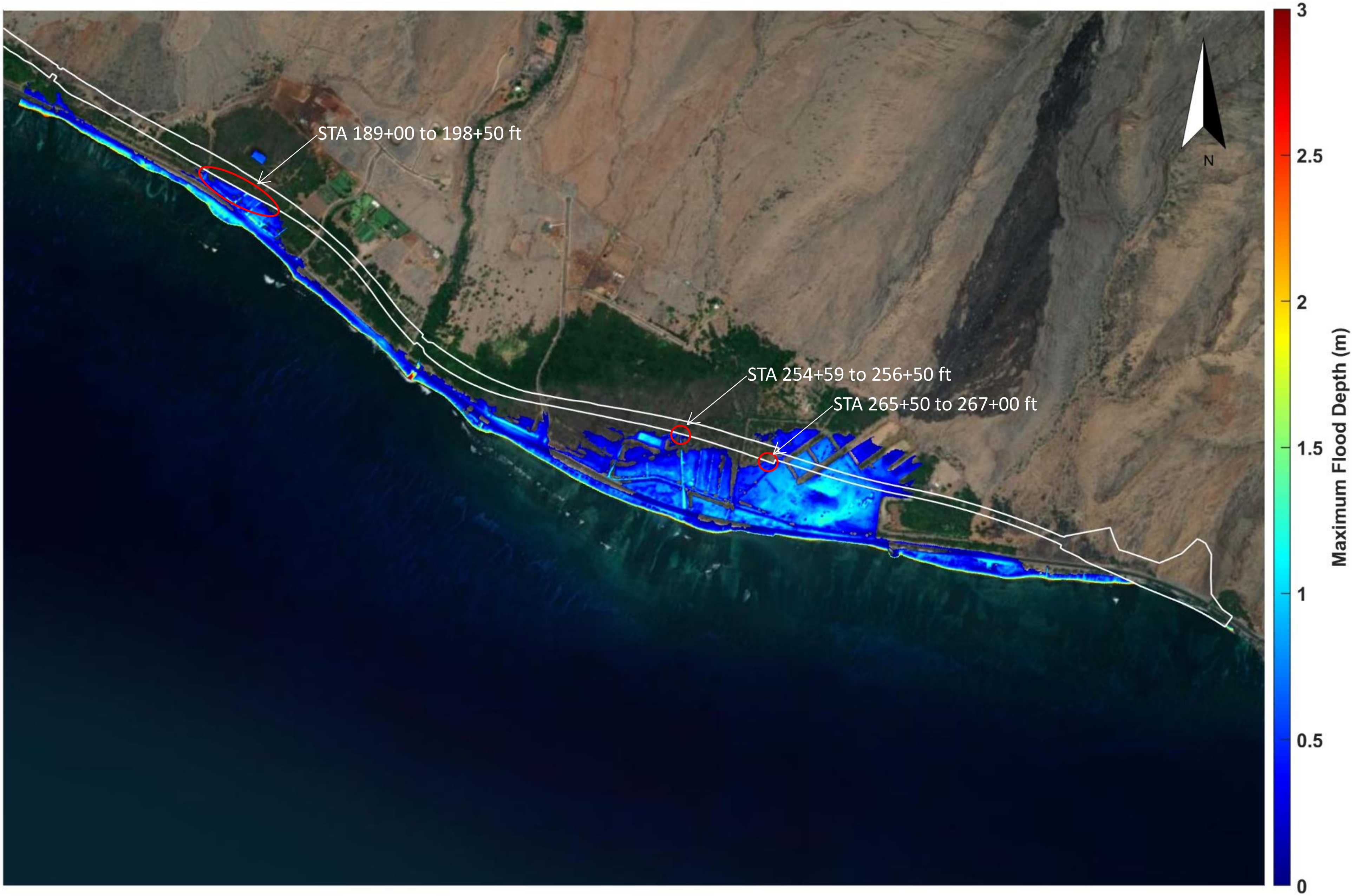


Figure C-1. XBeach-NH modeled maximum flood depth for alternative 1 alignment (Ukumehame)

Figure C-2. XBeach-NH modeled maximum flood elevation for alternative 1 alignment (Ukumehame)

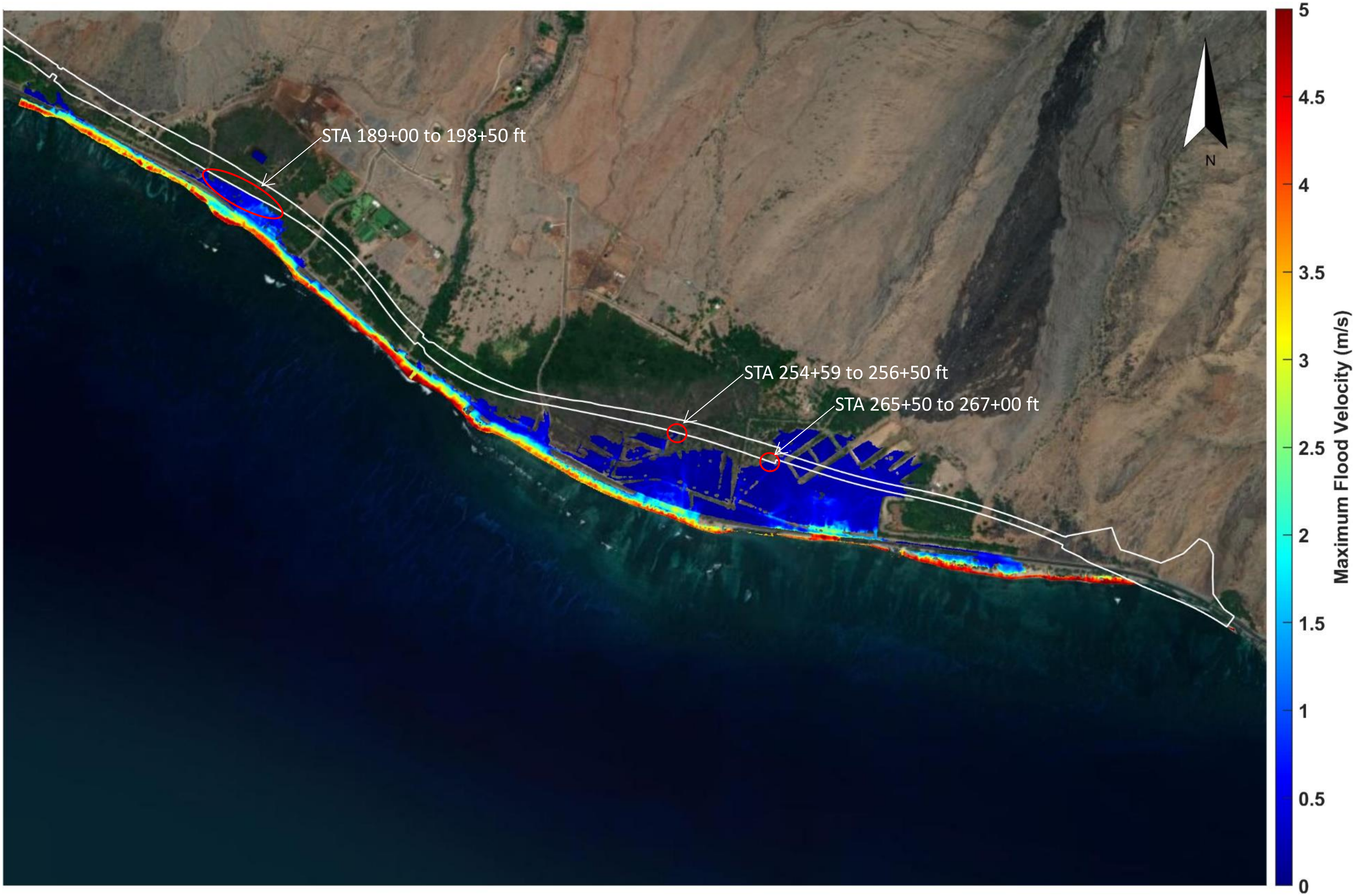


Figure C-3. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 1 alignment (Ukumehame)

Figure C-4. XBeach-NH modeled maximum flood depth for alternative 1 alignment (Olowalu)

Figure C-5. XBeach-NH modeled maximum flood elevation for alternative 1 alignment (Olowalu)

Figure C-6. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 1 alignment (Olowalu)

Appendix D:

XBEACH-NH MODELED FLOOD DEPTHS, ELEVATIONS, AND VELOCITIES – ALTERNATIVE 2 ALIGNMENT

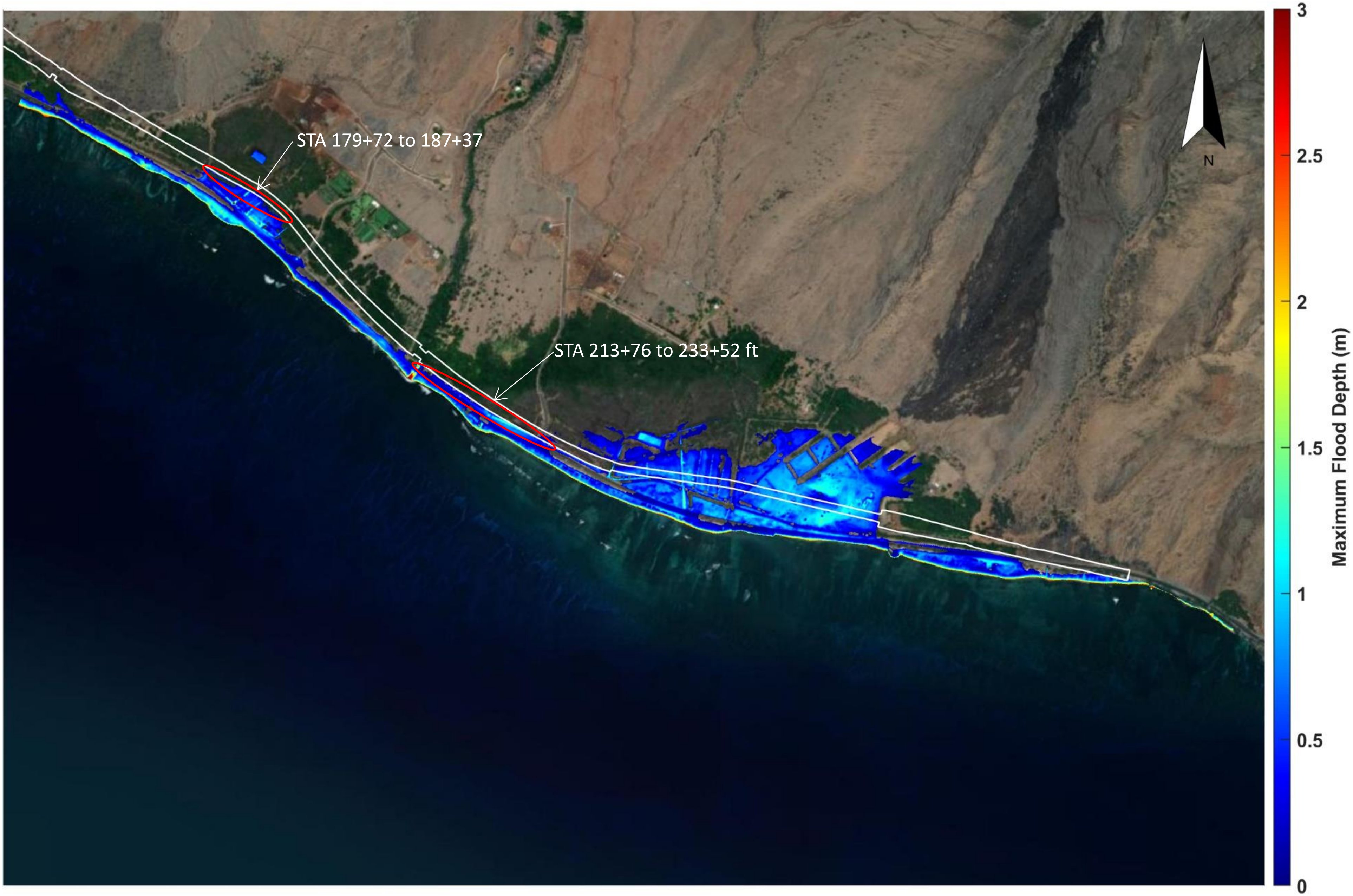


Figure D-1. XBeach-NH modeled maximum flood depth for alternative 2 alignment (Ukumehame)

Figure D-2. XBeach-NH modeled maximum flood elevation for alternative 2 alignment (Ukumehame)

Figure D-3. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 2 alignment (Ukumehame)

Figure D-4. XBeach-NH modeled maximum flood depth for alternative 2 alignment (Olowalu)

Figure D-5. XBeach-NH modeled maximum flood elevation for alternative 2 alignment (Olowalu)

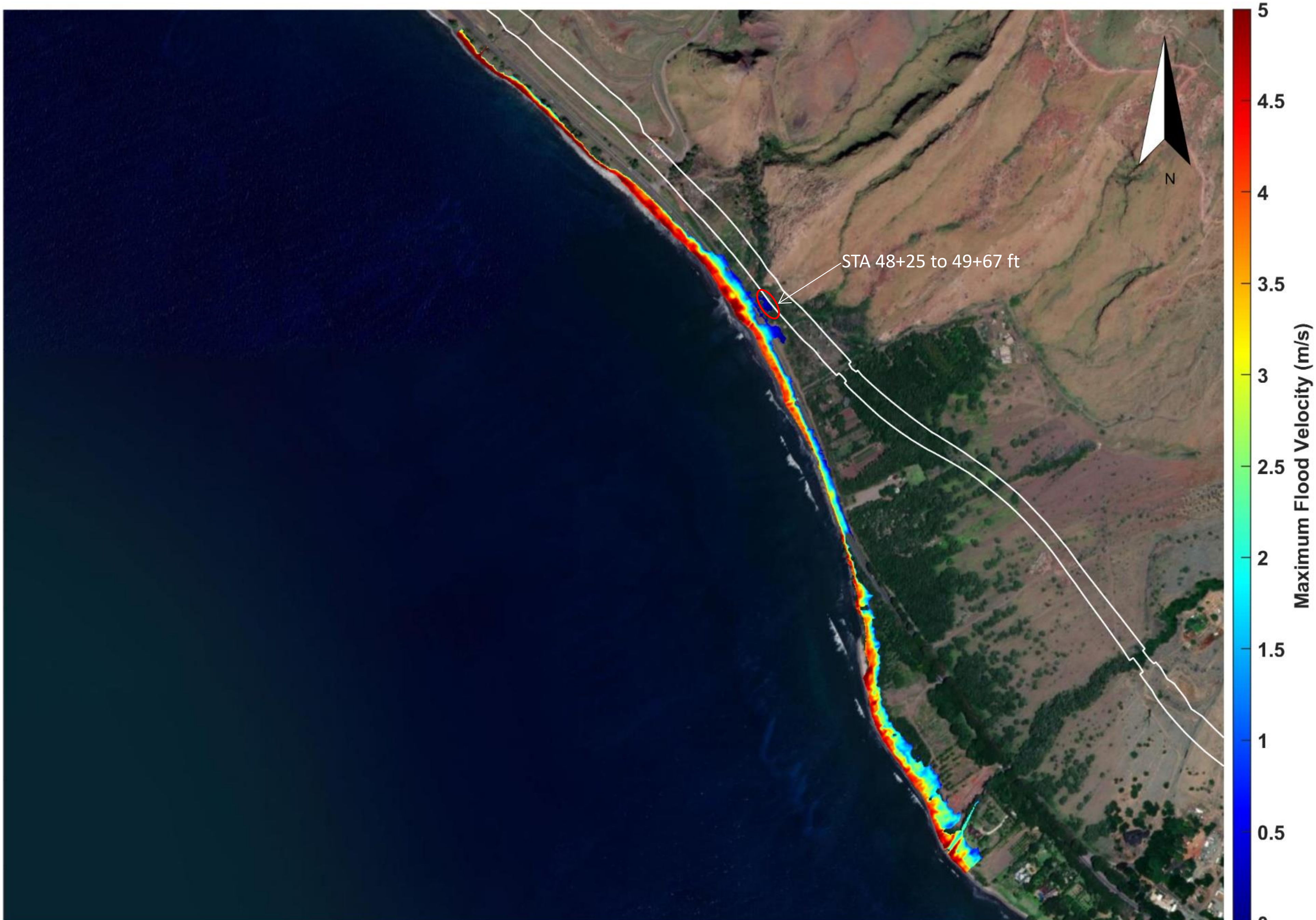


Figure D-6. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 2 alignment (Olowalu)

Appendix E:

XBEACH-NH MODELED FLOOD DEPTHS, ELEVATIONS, AND VELOCITIES – ALTERNATIVE 3 ALIGNMENT

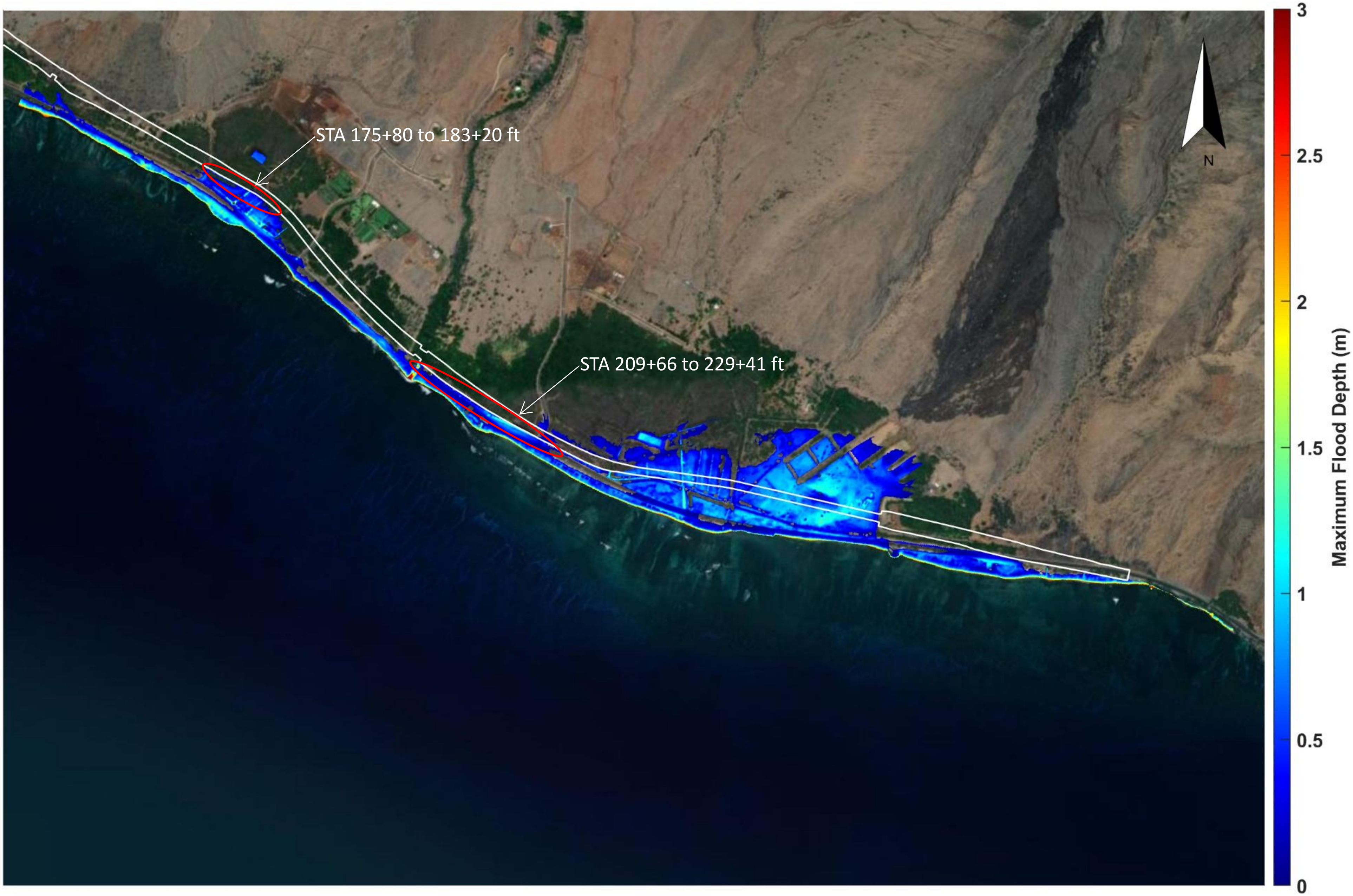


Figure E-1. XBeach-NH modeled maximum flood depth for alternative 3 alignment (Ukumehame)

Figure E-2. XBeach-NH modeled maximum flood elevation for alternative 3 alignment (Ukumehame)

Figure E-3. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 3 alignment (Ukumehame)

Figure E-4. XBeach-NH modeled maximum flood depth for alternative 3 alignment (Olowalu)

Figure E-5. XBeach-NH modeled maximum flood elevation for alternative 3 alignment (Olowalu)

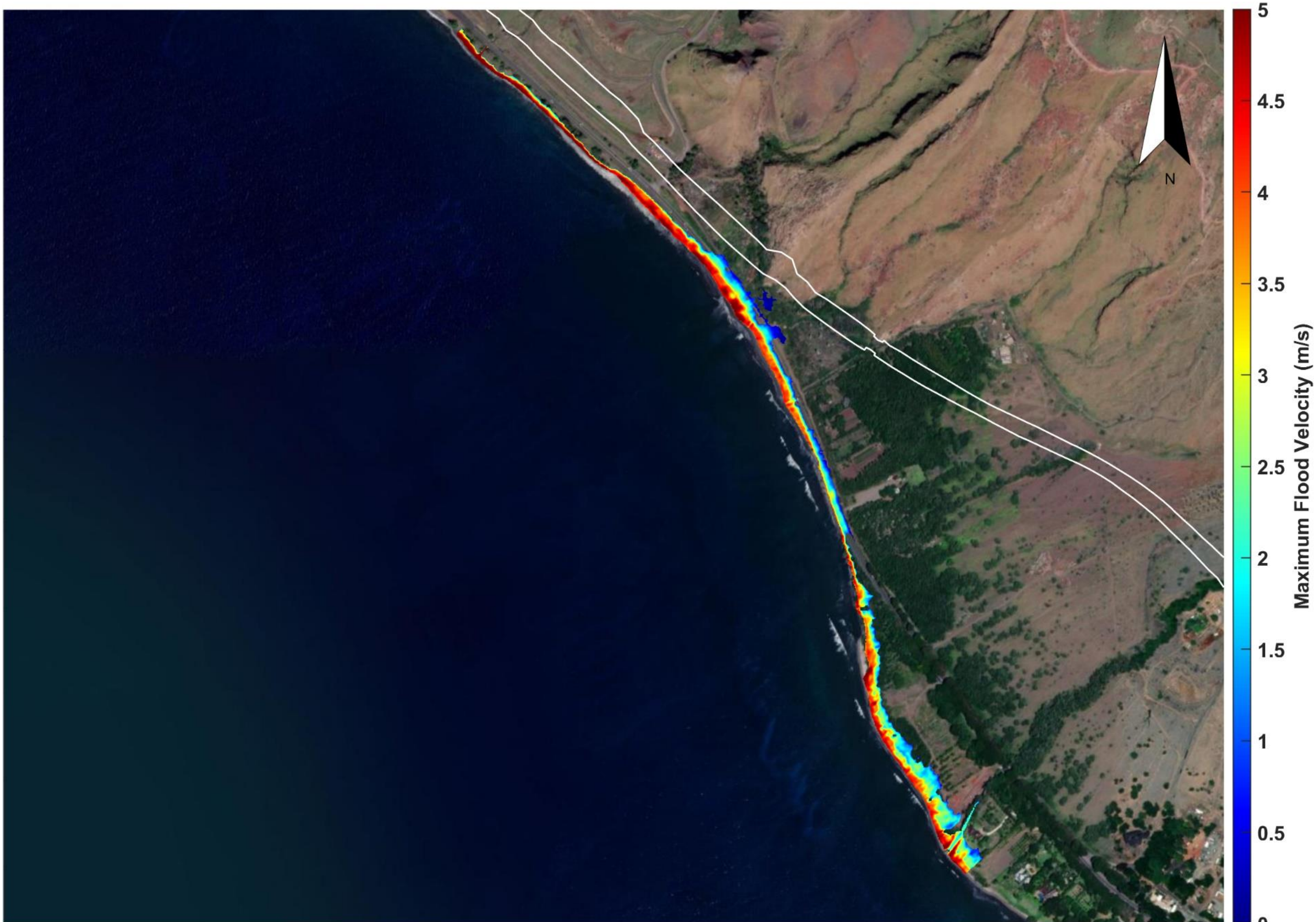


Figure E-6. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 3 alignment (Olowalu)

Appendix F:

XBEACH-NH MODELED FLOOD DEPTHS, ELEVATIONS, AND VELOCITIES – ALTERNATIVE 4 ALIGNMENT

Figure F-1. XBeach-NH modeled maximum flood depth for alternative 4 alignment (Ukumehame)

Figure F-2. XBeach-NH modeled maximum flood elevation for alternative 4 alignment (Ukumehame)

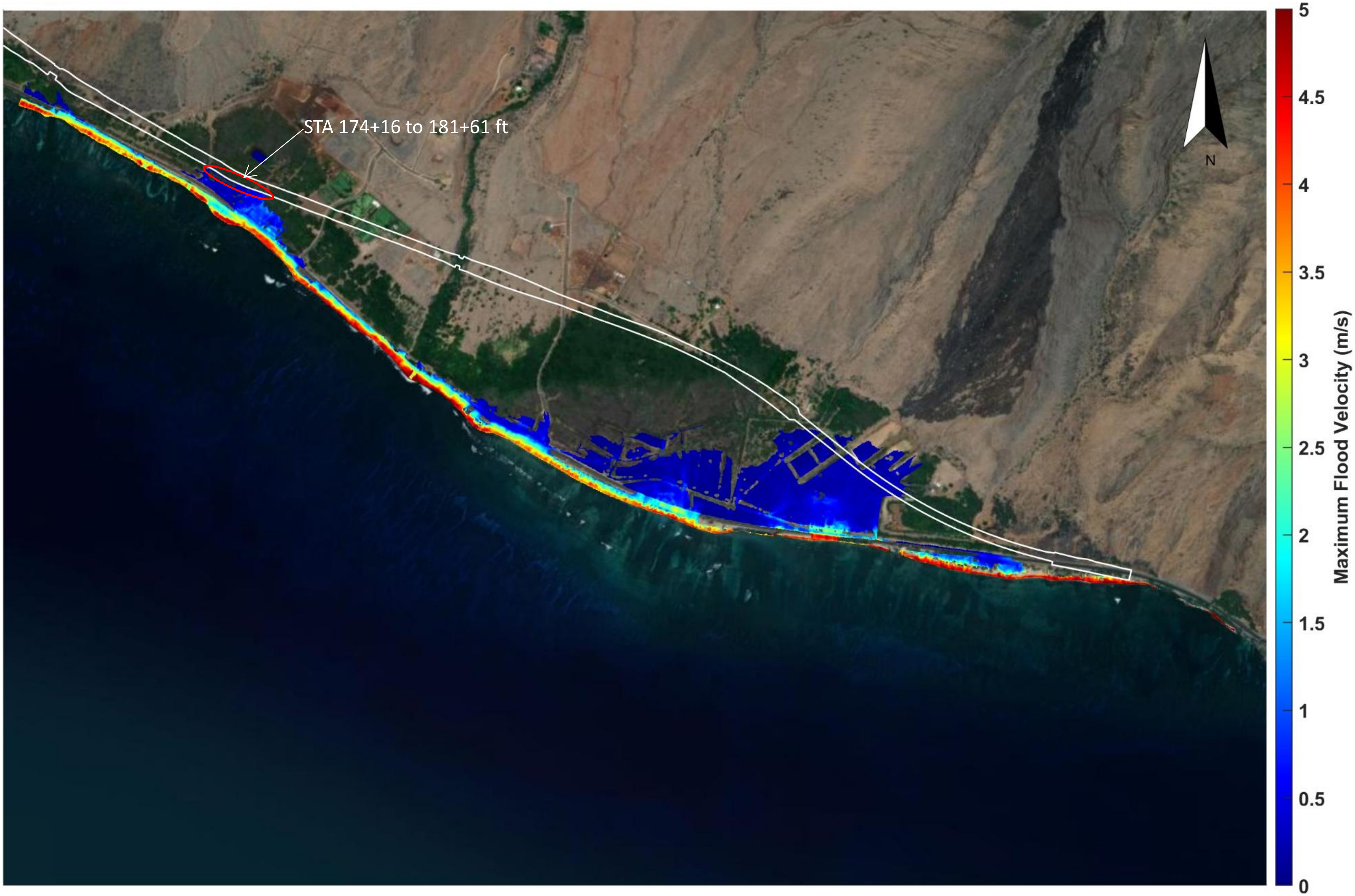


Figure F-3. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 4 alignment (Ukumehame)

Figure F-4. XBeach-NH modeled maximum flood depth for alternative 4 alignment (Olowalu)

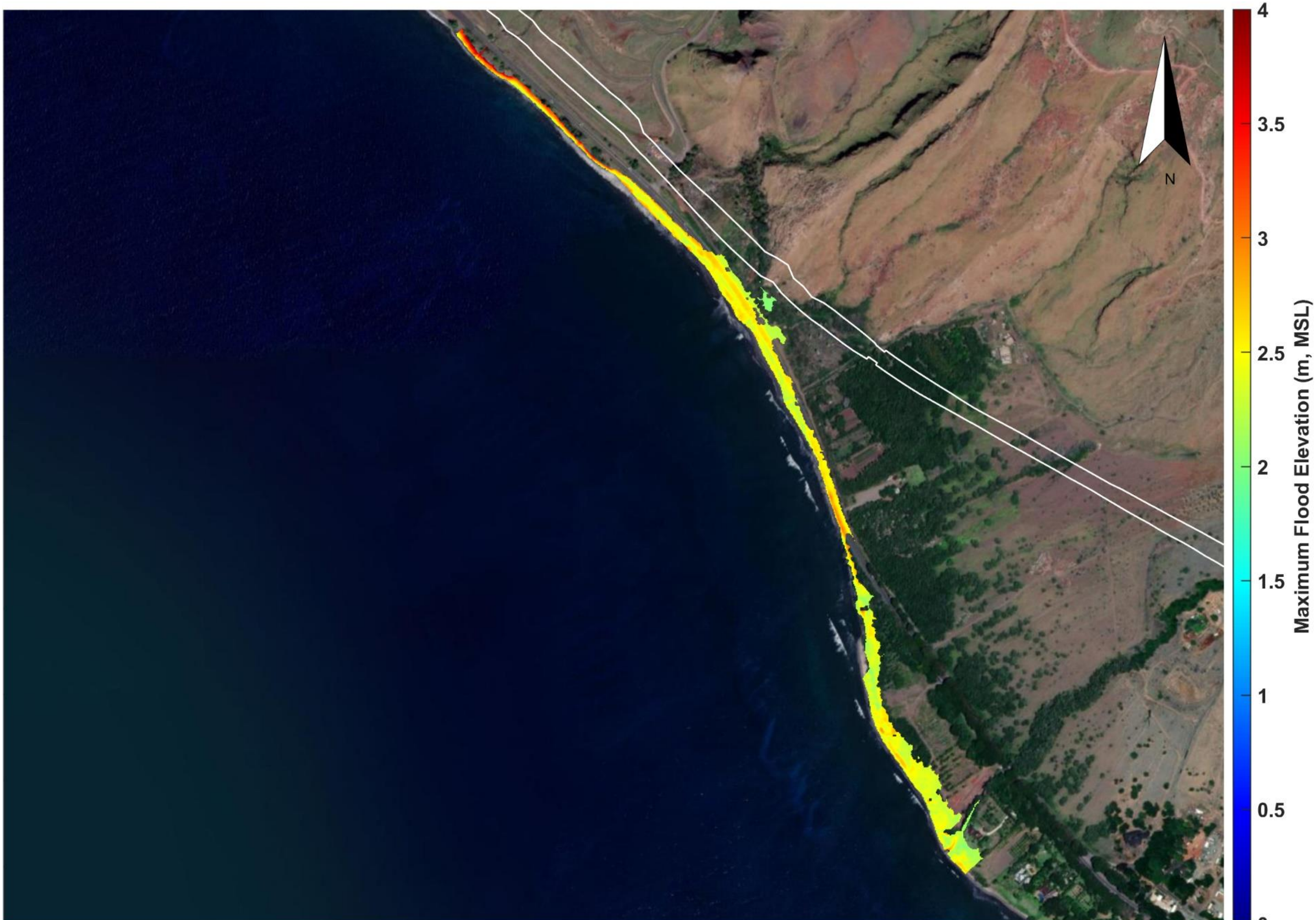


Figure F-5. XBeach-NH modeled maximum flood elevation for alternative 4 alignment (Olowalu)

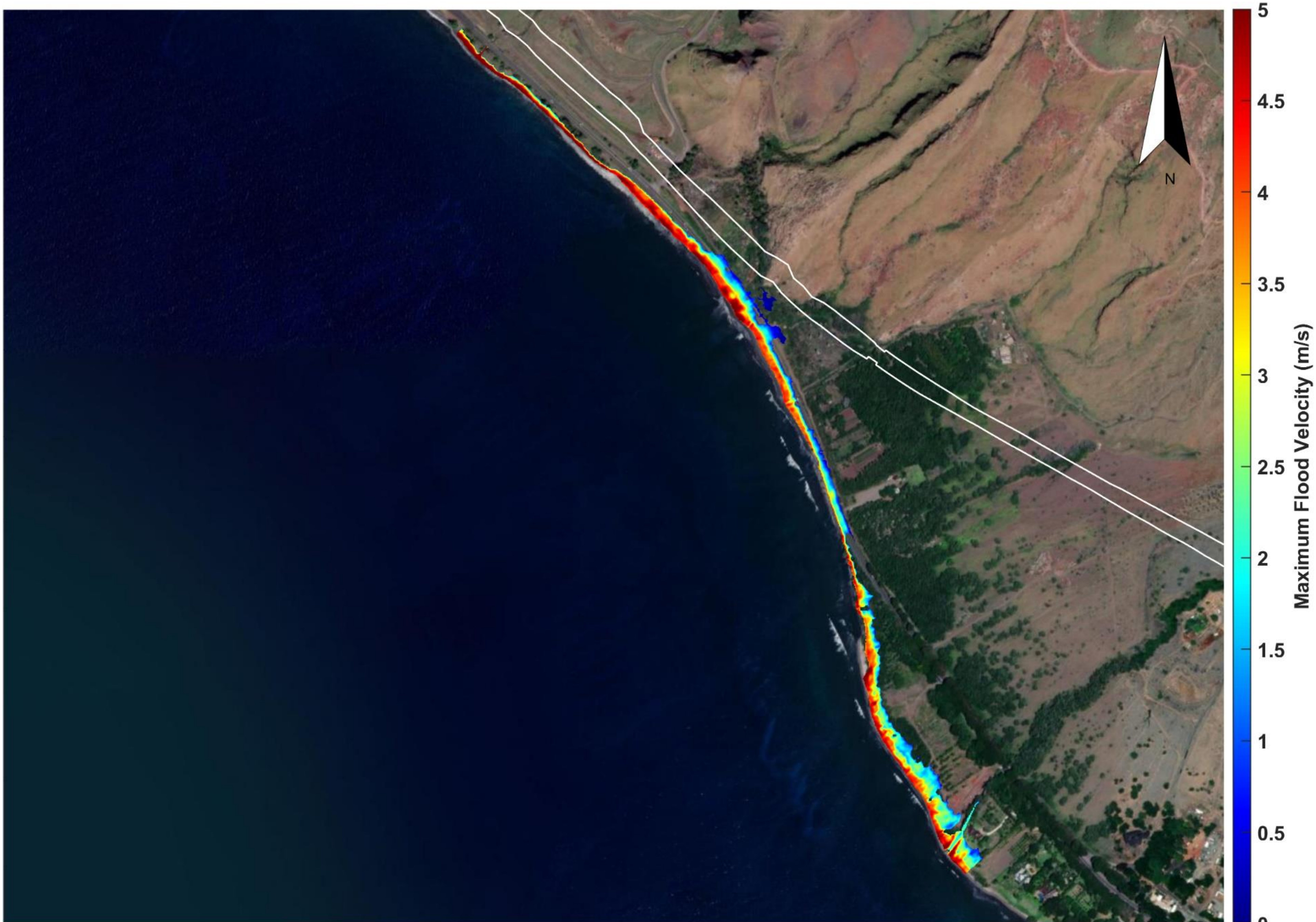


Figure F-6. XBeach-NH modeled maximum flood depth-averaged velocity for alternative 4 alignment (Olowalu)