DAILY, MONTHLY, AND YEARLY TIDAL FLOOD EVENTS DUE TO SEA LEVEL RISE

US HIGHWAY 101 HUMBOLDT BAY AREA

FINAL REPORT
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Problem Statement

Sea level rise (SLR) will directly impact Humboldt Bay by increasing the risk of shoreline overtopping from higher than average tides, resulting in flooding of low lying areas with sea water. This will render many lands unsuitable due to saltwater inundation. Our team will develop a series of predictive models of how sea level rise could affect increases in tidal flooding along US Highway 101 and the safety corridor, located between the cities of Eureka and Arcata. We will look at what lands will be temporarily flooded as well as permanently flooded. Our analysis will take into account predicted tidal patterns, SLR trends, the sublimation of Humboldt County, and tidal inundation curves. A series of maps and tables will be developed to determine events of flooding in and around US Highway 101. The results of our model will be used to predict the potential impacts associated with tidal flooding and inundation.

Background

Through technical innovation and centuries of hard work, we have reached a standard of living previously unheard of - largely attributed to our understanding of the natural world through the use of science. In recent years however, science has shown us that this progression has come at a cost to our environment. Climate change, an anthropogenic phenomenon caused by the release of greenhouse gases into our atmosphere is currently threatening life as we know it. Some have gone so far as to call climate change the biggest threat to humanity and the economy (Business, 2017). One metric of climate change is the atmospheric concentration of carbon dioxide. Referring to *figure 1* below, which shows the increase of atmospheric CO_2 from 1960 to 2010. We noticed there was only 320 parts per million (ppm) in 1960, and with a current concentration of over 405 ppm, we can see the trend in increasing emissions (NOAA, 2017).

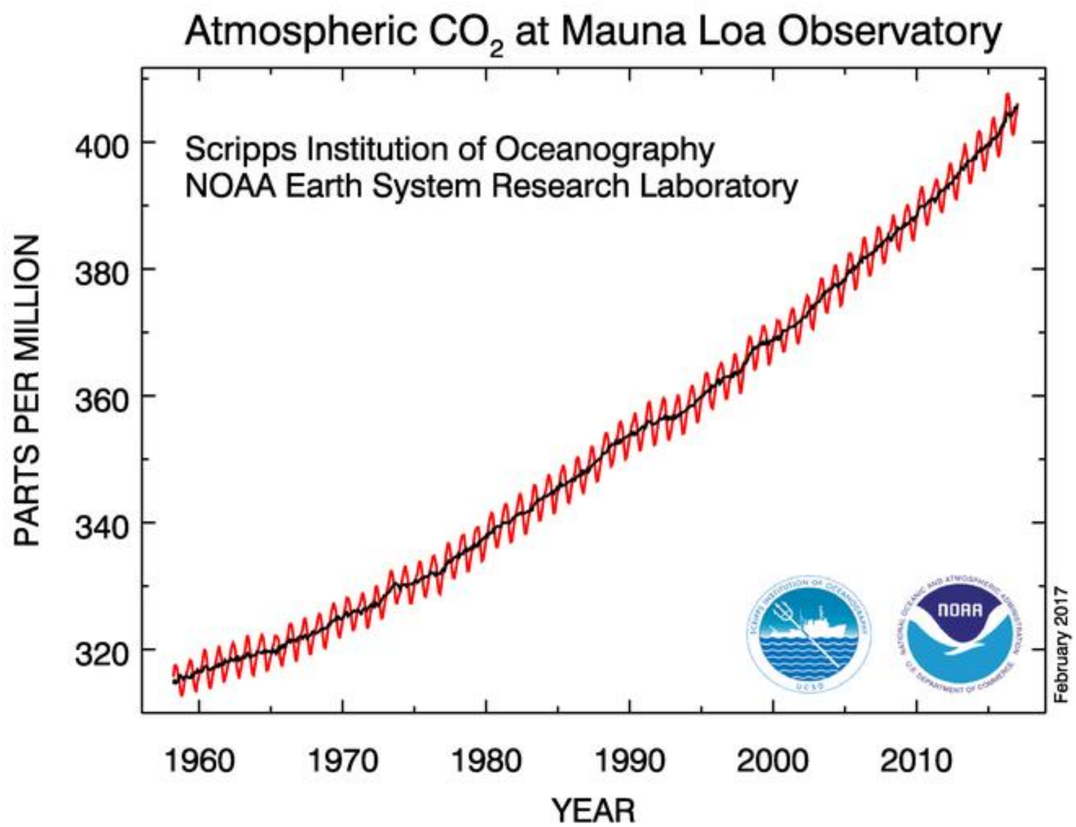

Figure 1: An apparent trend in Atmospheric CO2 at Mauna Loa Observatory from 1960's to 2015.

While an increase in global average surface temperature is expected from this rising trend in global CO_2 acceleration, there are also a slew of other impacts ranging from extreme drought, more extreme storms/precipitation, ocean acidification, and SLR. Climate change can cause SLR through two mechanisms. The first is through a process known as thermal expansion, or simply the enlargement of the ocean water itself due to an increase in temperature. The second mechanism is from the addition of water brought on by the melting of terrestrially-based ice sheets. While scientists have known that the sea level has risen steadily since 1900, they have recently concluded that it has been doing so at a rate of roughly 0.04 - 0.1 inches per year (NOAA, 2017). A recent realization of these findings has been the necessity to include these projections in infrastructure planning as well as adaptation planning strategies. It has been estimated that over 38% of the world's population, approximately 2.9 billion people, live within 100 km (60 miles) of an ocean coastline (Small, C., & Nicholls, R. et al., 2003). With this in mind, it is no wonder why this information is cause for concern as we plan for the future.

In 2008, Governor Schwarzenegger issued Executive Order S-13-08, the California Climate Adaptation Strategy, which identified the necessity to plan for and adapt to SLR. This bill was designed to make California more proactive in regards to climate change. Governor Schwarzenegger understood that the

> Longer that California delays planning and adapting to SLR the more expensive and difficult adaptation will be. California must begin now to adapt and build our [resilience] to coming climate changes through a thoughtful and sensible approach with local, regional, state and federal government using the best available science; and [WHEREAS] there is a need for statewide consistency in planning for SLR; and [WHEREAS] California's water supply and coastal resources, including valuable natural habitat areas, are particularly vulnerable to sea level rise over the next century and could suffer devastating consequences if adaptive measures are not taken (Schwarzenegger, 2008).

This executive order sparked a series of SLR analyses up and down the state of California in order to inventory and map existing shorelines, to look at the state of our coast line, and identify infrastructure that will be potentially affected due to rising sea levels.

In response, the State Coastal Conservancy (SCC) authorized funding for a multi-phase sea level rise adaptation planning effort for Humboldt Bay that was undertaken by Aldaron Laird at Trinity Associates (Laird, 2013). These projects have been successful in analyzing the potential impacts of sea level rise for the Humboldt Bay area and have been broken up into 3 phases. Phase I, completed in January of 2013, mapped and took inventory of Humboldt Bay's existing shoreline and assessed the Bay's vulnerability from projected SLR (Laird, 2013). Phase II, completed in February of 2015, focused on SLR adaptation and planning and analyzed the risks of flooding in low lying coastal areas of Humboldt Bay, with detailed focus on the City of

Eureka (Laird, 2015). Phase II also provided hydrodynamic modeling and inundation maps for various SLR scenarios (Anderson, 2015).

Phase III of the project is currently in progress. In 2016, the city of Eureka mapped every city asset that could potentially be affected by SLR and established a scale of risk for each (Laird, 2016a). Later that year a draft adaptation plan for Eureka developed adaptation goals, strategies, and measures for high priority assets for existing and future developments (Laird, 2016b).

Other work that has been done under the SCC was the development of a Digital Elevation Model (DEM) that continuously covered all of Humboldt Bay's subtidal, intertidal, and terrestrial areas by the Pacific Watershed Associates (PWA) in 2014 (Gilkerson, 2014). The Coastal Ecosystems Institute of Northern California modeled the effects of SLR on groundwater of Humboldt Bay (Willis, 2014). A preliminary data release was done for the Humboldt Bay Sea Level Rise Vulnerability Assessment: Humboldt Bay Sea Level Rise Inundation Mapping (Anderson, 2014).

Tides of Humboldt County

Humboldt Bay experiences two separate high tides and two separate low tides every day. These varying tides are referred to as a mixed semidiurnal tide and are displayed in *Figure 2* below. The average of the high tides are referred to as Mean Higher High Water (MHHW) and Mean High Water and the average of the low tides are referred to as Mean Lower Low Water and Mean Low Water. This study only looks at MHHW for daily inundation.

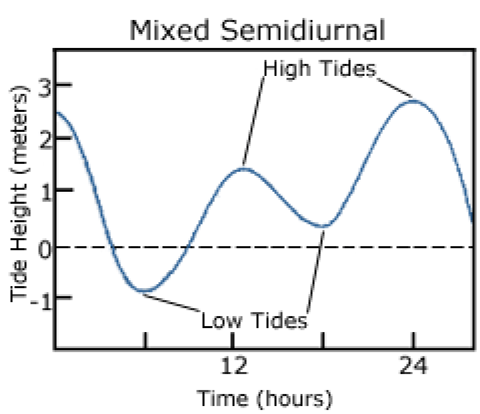

Figure 2: Graph shows average tide heights in a given lunar day for a mixed semidiurnal pattern (NOAA, 2008).

The monthly tidal patterns are caused by the combined effects of the sun and the moon on the Earth and are often referred to as Spring and Neap Tides. The average Spring tides for Humboldt Bay are known as the Mean Monthly Maximum Water (MMMW) and are monthly higher tides which are affected by gravity and exaggerate daily tidal patterns when the pull of the moon elevates tidal heights relative to the earth. Neap tides, also known as Mean Monthly Low Water, are low tide patterns which occur when the gravitational influence of the moon is perpendicular to the sun. This study looks at the MMMW for monthly flooding.

The yearly influences to tidal patterns are defined as Mean Annual Maximum Water (MAMW) which represents the average of high tide events for the year. The annual tidal patterns are influenced by larger non-localized yearly weather events and thermal convection currents, as displayed in figure 3. Forces such as the El Nino and La Nina Southern Oscillations fuel weather patterns such as winds, atmospheric moisture content, barometric pressure, water temperature and a host of other local and non-localized forces which influence Humboldt's tidal patterns," (Merrifield et al., 2013). This study looks at MAMW for yearly flooding.

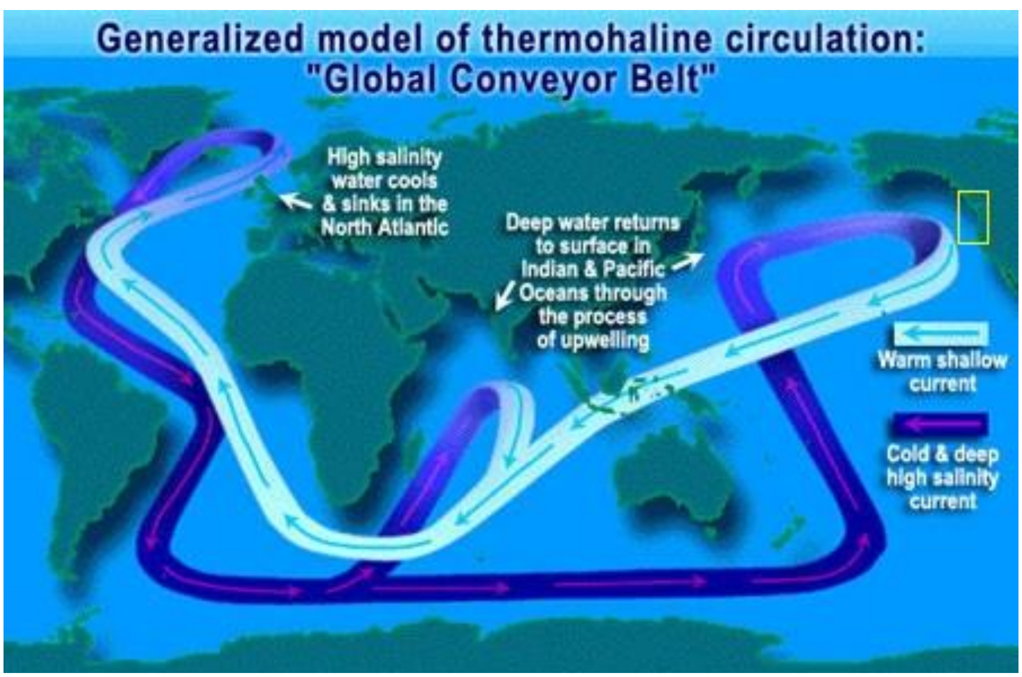

Figure 3: Global current patterns from thermohaline circulation that affect MAMW.

("Environment : Climate | National Snow and Ice Data Center," 2017).

Land Sublimation of Humboldt Bay

Another factor that must be considered when looking at sea level rise is the change of land elevation from tectonic activity because "Humboldt Bay is subsiding (-0.09 inches/yr.) and its average rate of relative sea level rise is 0.18 inches/year (18 inches per century), which is greater than anywhere else in California" (Laird, 2016). The additional sublimation of Humboldt Bay has accelerated the rate of land loss and seawater inundation due to sea level rise. This means that Humboldt Bay must be proactive in response to SLR instead of reactive.

Sea Level Rise Projections

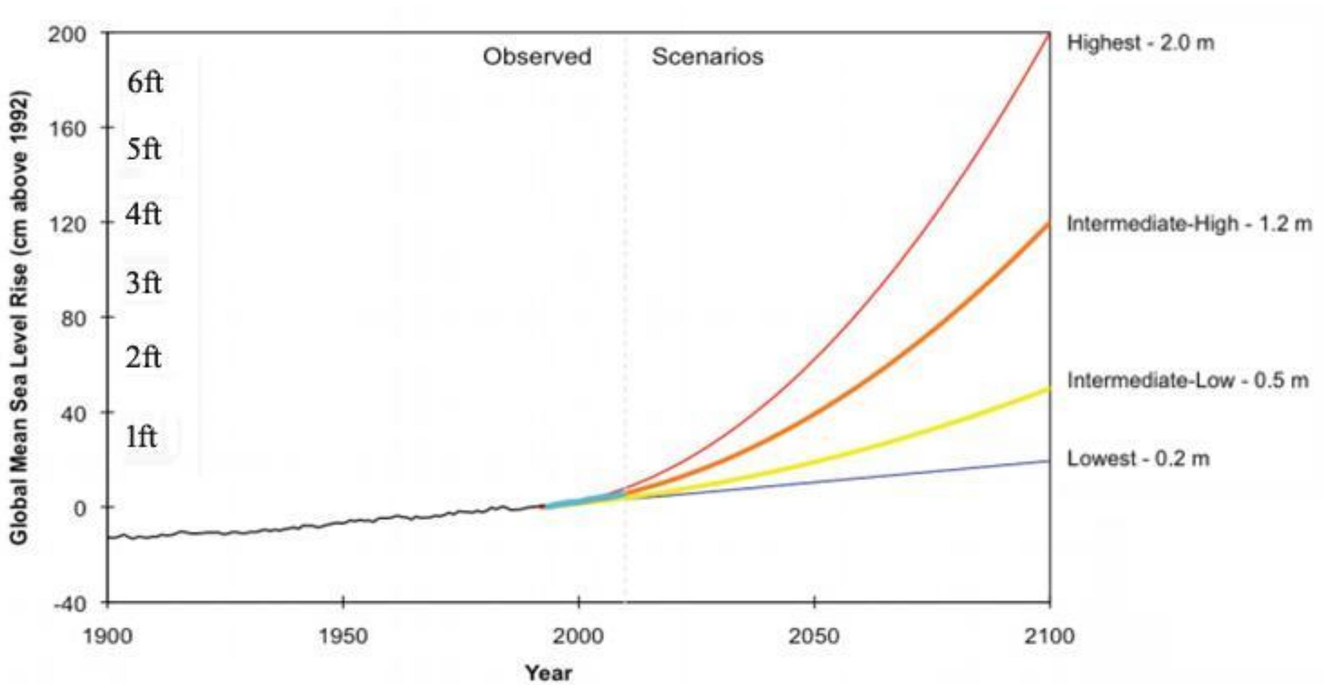

Figure 4: Global Mean Sea Level Rise Projection Scenarios to 2100 with observed sea levels since 1900.

Different projections of SLR have been determined and are based on varying calculations and methodology and these scenarios are found in *Figure 4*. This study looks at a high, medium, and low projections specific to Humboldt Bay for the analysis.

Similar Research

While geospatial analysis and climate change sciences are still in their early years of development, they have already merged to offer fantastic results. One such study published by Ocean & Coastal Management utilized LiDAR data to model and visually display the results of a rising sea level's impact on a United Kingdom estuary. This team used ground-truthed LiDAR data in conjunction with a 'pour-point' flood modelling method in order to simulate tidal inundation in the UK. This study is significant in both its scope and level of detail. The team conducting the study ran models for both tidal inundations under current projections, and tidal inundations with large-scale engineering features in order to quantify the results of structural mitigation efforts. Their study concluded that through the alteration of landscape features, the land which was to be previously inundated could vary by over 20%, or slightly more than 100 hectares (Krolik-Root et al., 2015).

Another similar study conducted utilizes geospatial analysis to examine the relationship between tidal inundation and salt marsh vegetation distribution in Australia. The team used fine scale elevation data, field surveys, and high precision global positioning systems (GPS) to obtain horizontal mapping accuracy. This study is significant because the team successfully modelled areas of land which were to be inundated, as well as the frequency and extent of such occurrences. The conclusion from this study was that their spatial analysis methods applied "...depicted variations in inundation patterns under the different tidal phases that influence physiological conditions throughout the wetland" (Hickey, 2010). A similar study would be desirable for Humboldt Bay and would further our analysis on the effects of SLR in the region.

Data, Tools, and Preliminary Info

Preliminary Info

A seawater inundation analysis was performed on US Highway 101, focused on four subsections of the 101 between Hookton Slough and the city of Arcata. The area from Hookton Slough to King Salmon (KSH) has been previously identified in Laird's (2013) Humboldt Bay Shoreline Inventory as a low lying land that is predicted to become inundated from SLR and that is why it was chosen as a region of interest in this study. The US Highway 101 safety corridor between Eureka and Arcata was also previously identified as a low lying land that is predicted to become inundated from SLR. This section of the highway is a main thoroughfare for the region, and due to its importance has been broken up into three sections for detailed analysis. Eureka Slough (ES) is just east of Highway 101 and this section was chosen specifically to look at back-flooding from the slough. The rest of the safety corridor was split at the Brainard Industrial Park creating the Eureka Slough to Brainard (ESB) section and the Brainard to Arcata (BA) section. These sections can be found in *Figure 5*.

Figure 5: Locator map for the four areas of study along the 101 corridor.

All spatial data was projected to UTM Zone 10 WGS84. The vertical datum used for sea levels was North American Vertical Datum of 1988 (NAVD88).

Prior studies created inundation maps of Humboldt Bay that show where projected sea levels will affect Humboldt Bay based on the developed mean high water (MHW) shoreline and existing conditions as of 2012, with 0.5 meter (50 cm) increments. Each of these scenarios include maps showing MMMW, MAMW, 10-year flooding events, and 100-year recurrence interval extreme water levels. This provided baseline data and information for the analysis.

Data

- 1 meter resolution digital elevation model (DEM) that shows both topographic and bathymetric elevation of Humboldt Bay created by Pacific Watershed Associates. This was a crucial piece of data for this project.
- Polygon shapefiles of Highway 101.
- Sea level rise values, Located in Appendix 2.

Tools

For our analysis the following tools were used:

- ESRI's ArcMap 10.2

  ArcMap's Raster Calculator, Raster analysis tools, and spatial analysis tools were used for analysis of this project. It was also used to create the map products.
- Python Scripting - WingIDE

  A python script was created to automate the analysis process. It ran each scenario of sea level rise and tide height to create raster data showing Highway 101's inundation locations. The code was written using WingIDE 5.1, a python shell.
- Google Earth Pro

  Google Earth Pro was used to visualize the data and create the boundaries of the study.

Analysis Methods

US Highway 101 was broken up into 4 sections. The sections from south to north are: King Salmon to Hookton Slough (KSH), Eureka Slough (ES), Eureka Slough to Brainard (ESB) and Brainard to Arcata (BA). These sections can be viewed in *Figure 5* above. Sea level rise values for each section were found using Humboldt Bay Sea Level Rise Hydrodynamic Modeling and Inundation Vulnerability Mapping Report SCC and Coastal Ecosystems in Northern California, prepared by Northern Hydrology and Engineering. Utilizing Google Earth Pro, we were able to pull up the hydrodynamic model for Humboldt Bay as seen in figure 6 below.

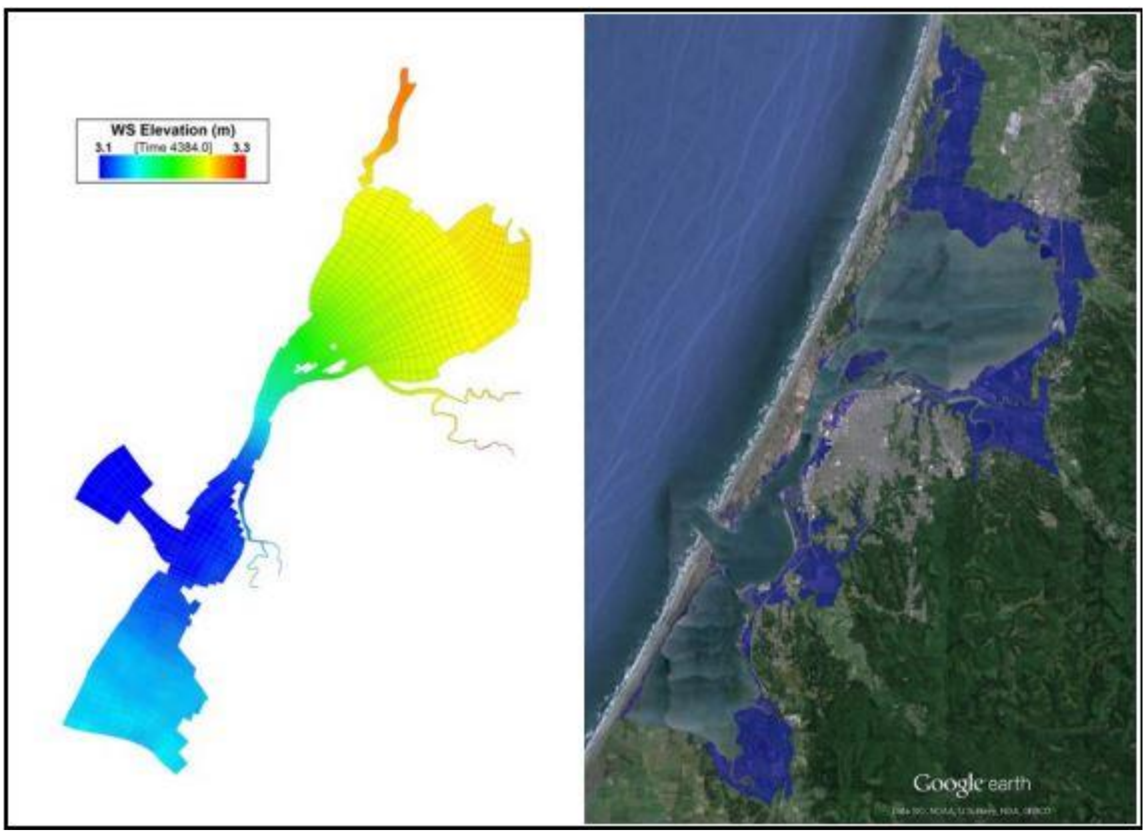

Figure 6: The hydrodynamic tidal model built by Northern Hydrology and Engineering. Humboldt Bay is split into approximately 1,600 individual cells.

We then determined which reference cells would be important to our analysis. We picked cells that spanned each separate area of interest, with one cell at the beginning, end, and several in the middle. These values were then averaged to determine the average SLR and tidal water levels, as Humboldt Bay does not have a uniform water level. This allowed our analysis to be more accurate as we tailored our SLR values to the actual water height in each area of study.

Those unique values were used in ArcMap's Raster Calculator tool to determine the extent of flooding in each section for the different scenarios. With each sea level rise projection, we analyzed: annual king tide flood events (MAMW), monthly Neap flood events (MMMW), and daily high tide flood events (MHHW). The entire process is found in *Figure 7*. This process was semi-automated using a python script. For each scenario an inundation flooding map was created to highlight which areas will be the most vulnerable to seawater intrusion and when. All of these maps can be found in Appendix 1.

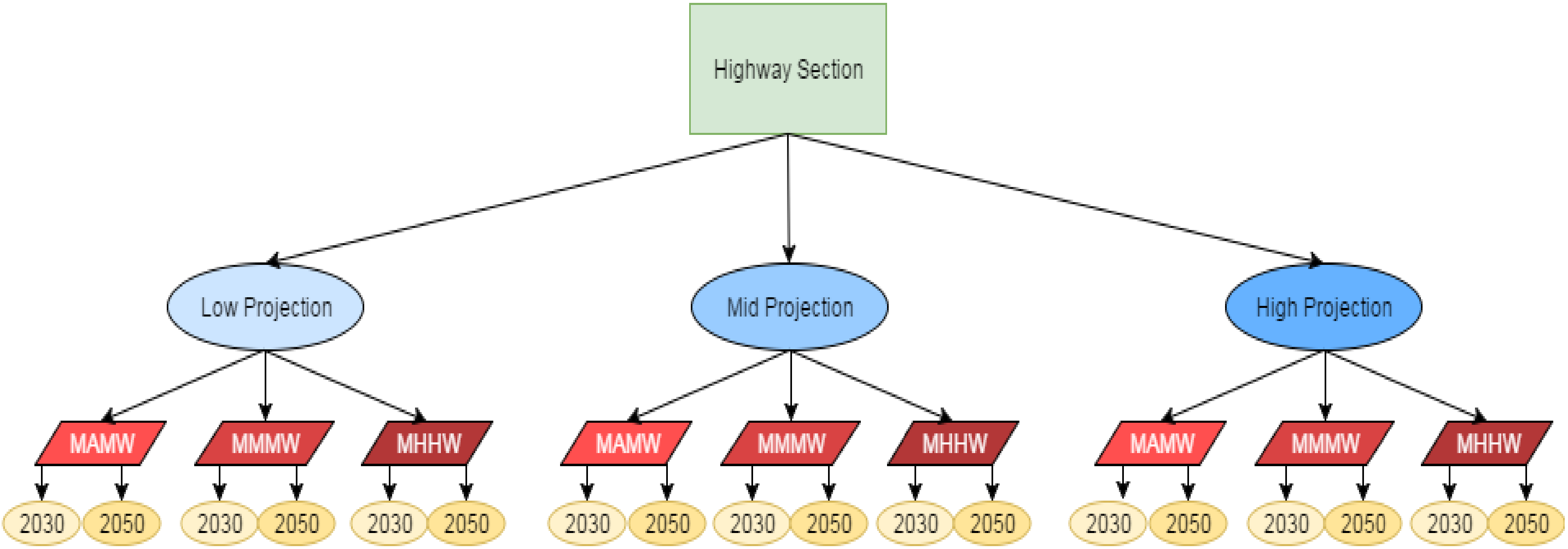

Figure 7: Flowchart depicting the breakdown of the steps for the analysis. This was done for each of the 4 sections.

Table 1: Table showing tide heights for different sea level rise projection thresholds - high, medium, and low. All values are in feet and are based on the NAVD88 vertical datum. These values were determined using predicted tidal patterns. Tidal height tables for the areas of study are located in Appendix 2. RSLRHP- Relative Sea Level Rise to the Humboldt Plate, MLLW- Mean Lower Low Water, MSL-Mean Sea Level, MHW-Mean High Water

YEAR	**RSLRHP**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**	**MMMW**	**MAMW**
2015	0	-0.3	0.9	3.4	5.8	**6.5**	**7.7**	**8.8**
2030	0.9	0.6	1.8	4.3	6.7	**7.4**	**8.6**	**9.7**
2050	1.9	1.6	2.8	5.3	7.7	**8.4**	**9.6**	**10.7**
YEAR	**RSLRMP**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**	**MMMW**	**MAMW**
2015	0	-0.3	0.9	3.4	5.8	**6.5**	**7.7**	**8.8**
2030	0.6	0.3	1.5	4	6.4	**7.1**	**8.3**	**9.4**
2050	1.1	0.8	2	4.5	6.9	**7.6**	**8.8**	**9.9**
YEAR	**RSLRLP**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**	**MMMW**	**MAMW**
2015	0	-0.3	0.9	3.4	5.8	**6.5**	**7.7**	**8.8**
2030	0.4	0.1	1.3	3.8	6.2	**6.9**	**8.1**	**9.2**
2050	0.7	0.4	1.6	4.1	6.5	**7.2**	**8.4**	**9.5**

Results

The sections below show the individual results of sea water inundation for each of the areas of study.

Meters^2 and percentage of Highway 101 Inundation - for 2030

Highway 101 Section	Low Projection Sea Level Rise			Mid Projection Sea Level Rise			High Projection Sea Level Rise			
	MHHW	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**Total Area**
Eureka Slough to Brainard	0.150383	1,067.20	17,279.09	0.744524	2,052.70	21,583.17	2.319617	4,061.45	24,404.46	27,049.65
	0.001%	3.945%	63.879%	0.003%	7.589%	79.791%	0.009%	15.015%	90.221%	
King Salmon to Hookton Slough	364.7813	17,173.85	41,477.78	652.936765	21,965.70	43,131.02	2,181.96	32,988.06	47,302.12	169,913
	0.215%	10.107%	24.411%	0.384%	12.928%	25.384%	1.284%	19.415%	27.839%	
Brainard to Arcata	1,705.43	3,243.27	25,354.31	1,755.79	4,431.30	29,740.78	1,931.16	9,802.59	39,322.29	168,699.78
	1.011%	1.923%	15.029%	1.041%	2.627%	17.629%	1.145%	5.811%	23.309%	
Eureka Slough	3,935.87	4,497.53	11,288.62	3,947.94	4,795.69	13,780.59	3,965.42	5,452.53	20,511.46	95,650.14
	4.115%	4.702%	11.802%	4.127%	5.014%	14.407%	4.146%	5.700%	21.444%	

Table 2: Highway 101 was divided into 4 parts. The area is in m2 of the highway that will be inundated by MHHW, MMMW, and MAMW for low, mid, and high projections of sea level rise for 2030.

Meters^2 and percentage of Highway 101 Inundation - for 2050

Highway 101 Section	Low Projection Sea Level Rise			Mid Projection Sea Level Rise			High Projection Sea Level Rise			
	MHHW	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**Total Area**
Eureka Slough to Brainard	12.64841	3,254.28	23,913.04	132.697	10,599.48	26,799.69	4527.89	25,987.96	27,049.65	27,049.65
	0.047%	12.031%	88.404%	0.491%	39.185%	99.076%	16.739%	96.075%	100.000%	
King Salmon to Hookton Slough	1179.691	27,567.98	45,126.32	3965.970611	36,975.49	49,532.75	24,585.67	47,404.61	58,906.37	169,913
	0.694%	16.225%	26.558%	2.334%	21.761%	29.152%	14.470%	27.899%	34.669%	
Brainard to Arcata	1,835.49	6,858.87	34,238.12	2,102.72	14,916.29	44,661.45	7,138.38	39,345.95	61,348.72	168,699.78
	1.088%	4.066%	20.295%	1.246%	8.842%	26.474%	4.231%	23.323%	36.366%	
Eureka Slough	3,962.42	5,324.92	16,281.80	4,001.92	7,877.09	22,667.83	4,869.83	20,270.07	33,306.04	95,650.14
	4.143%	5.567%	17.022%	4.184%	8.235%	23.699%	5.091%	21.192%	34.821%	

Table 3: Highway 101 was divided into 4 parts. The area in m2 of the highway that that will be inundated by MHHW, MMMW, and MAMW for low, mid, and high projections of sea level rise for 2050.

We found that The Eureka Slough - Brainard study area was the most susceptible to annual flooding events, where 63.8%-90.2% of the roadway would be flooded, while King Salmon to Hookton would see the most SLR on a monthly scale, 10.1%-19.4%. Eureka Slough would experience 4% of the highway surface flooding daily. For all highway sections, the low SLR projection values for daily and monthly tidal events were negligible in the 2030 model when compared to 2050.

The predictive values for the 2050 sections displayed which study areas were the most susceptible to rising sea levels at MHHW, MMMW, and MAMW. It showed substantial tidal flooding in all study areas for monthly tidal flood events, with the highway experiencing flooding on 4% - 96% of the roadway, and yearly flooding covering 17%-100% of the roadway. Daily flooding occurs in all highway sections, ranging from 0.7% flooding to 14.5% of the surface experiencing flooding, with the exception of Eureka Slough-Brainard. In this section of highway we see a small amount of daily flooding in the low and mid projection, 0.05% and 0.5% respectively, but then in the high projections, the amount of highway that is flooded increases to 16.7%.

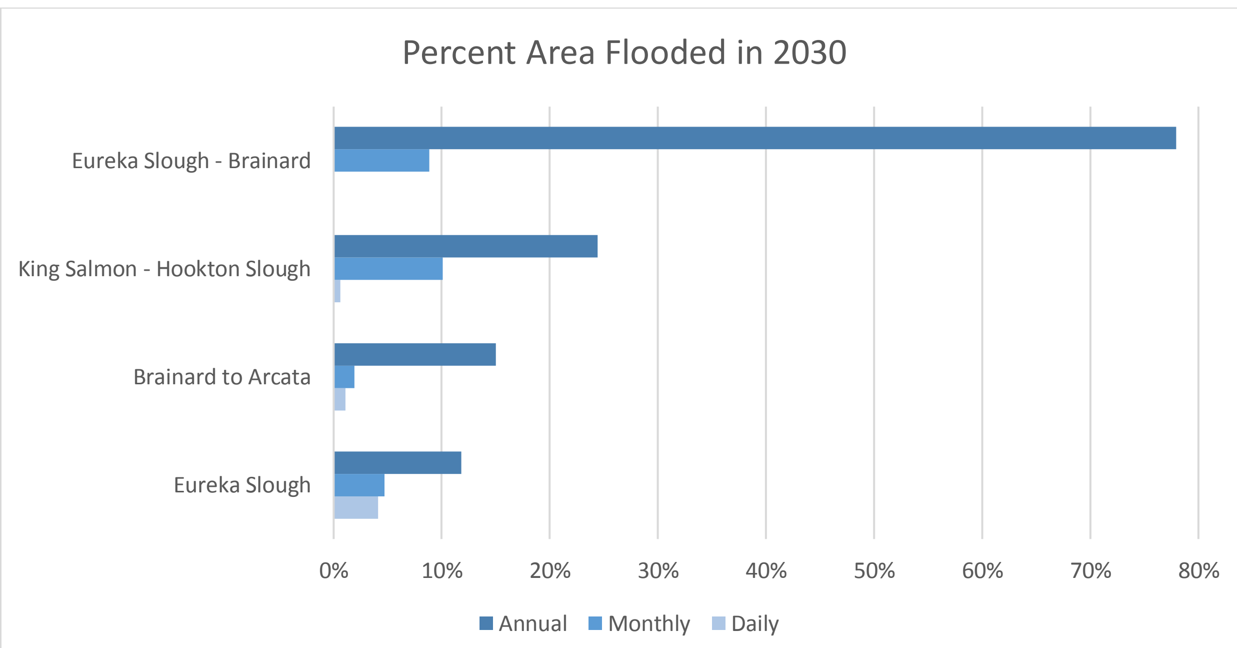

Figure 8: Shows the overall area flooded in 2030 for each area of study.

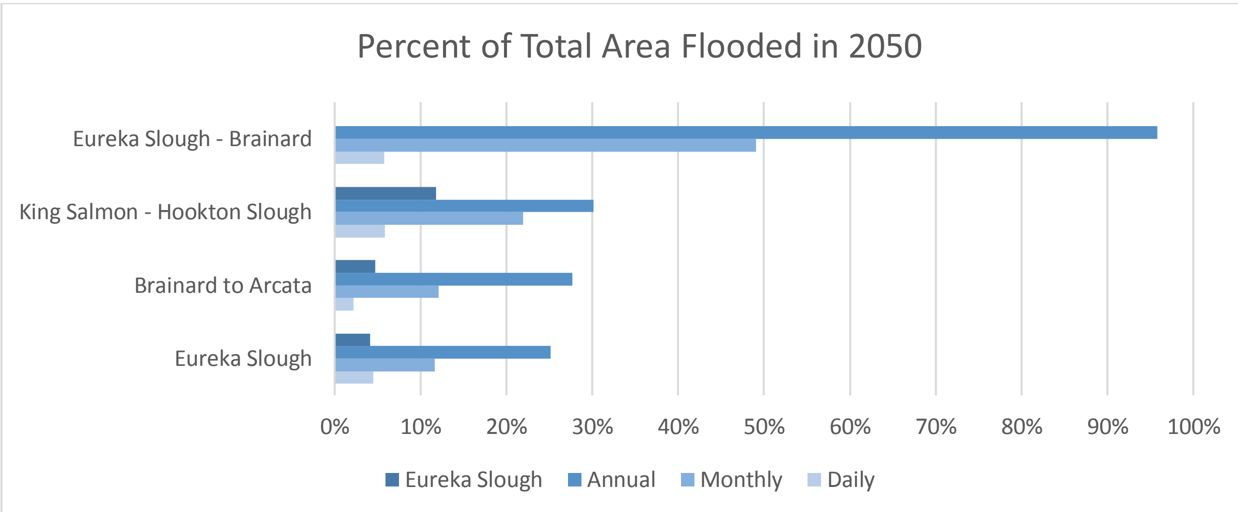

Figure 9: Shows the overall area flooded in 2050 for each area of study.

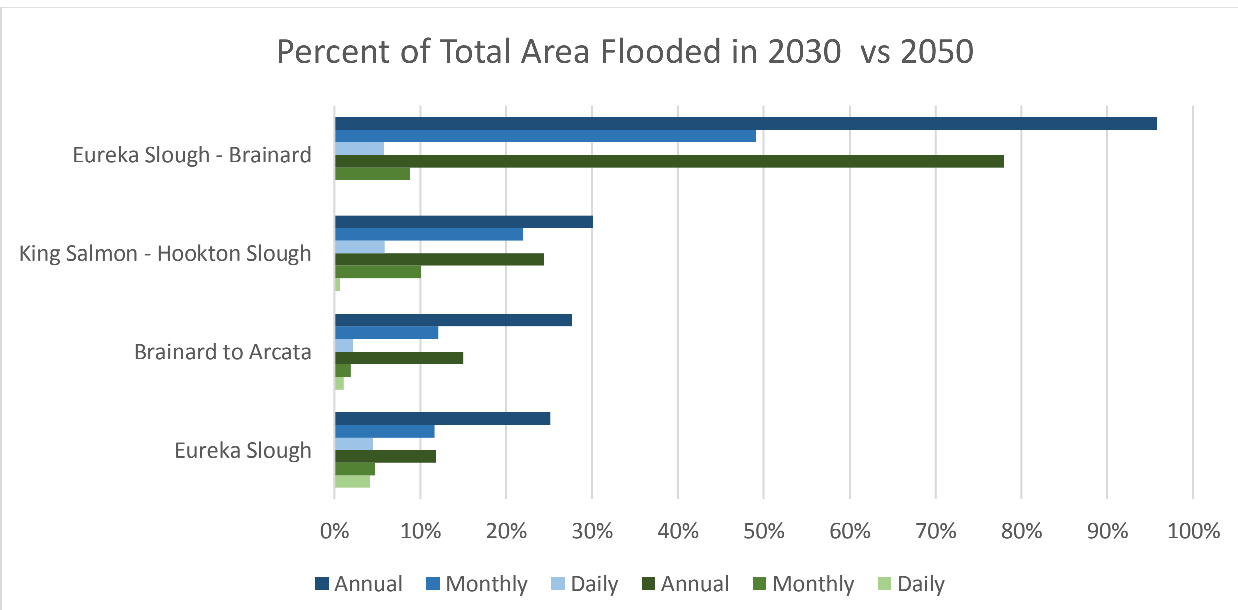

Figure 10: Shows the overall area flooded in 2030 and 2050 for each area of study. 2030- Blue, 2050- Green

Highway Section Arcata Eureka Corridor:

2030 Mid Sea Level Rise Projection:

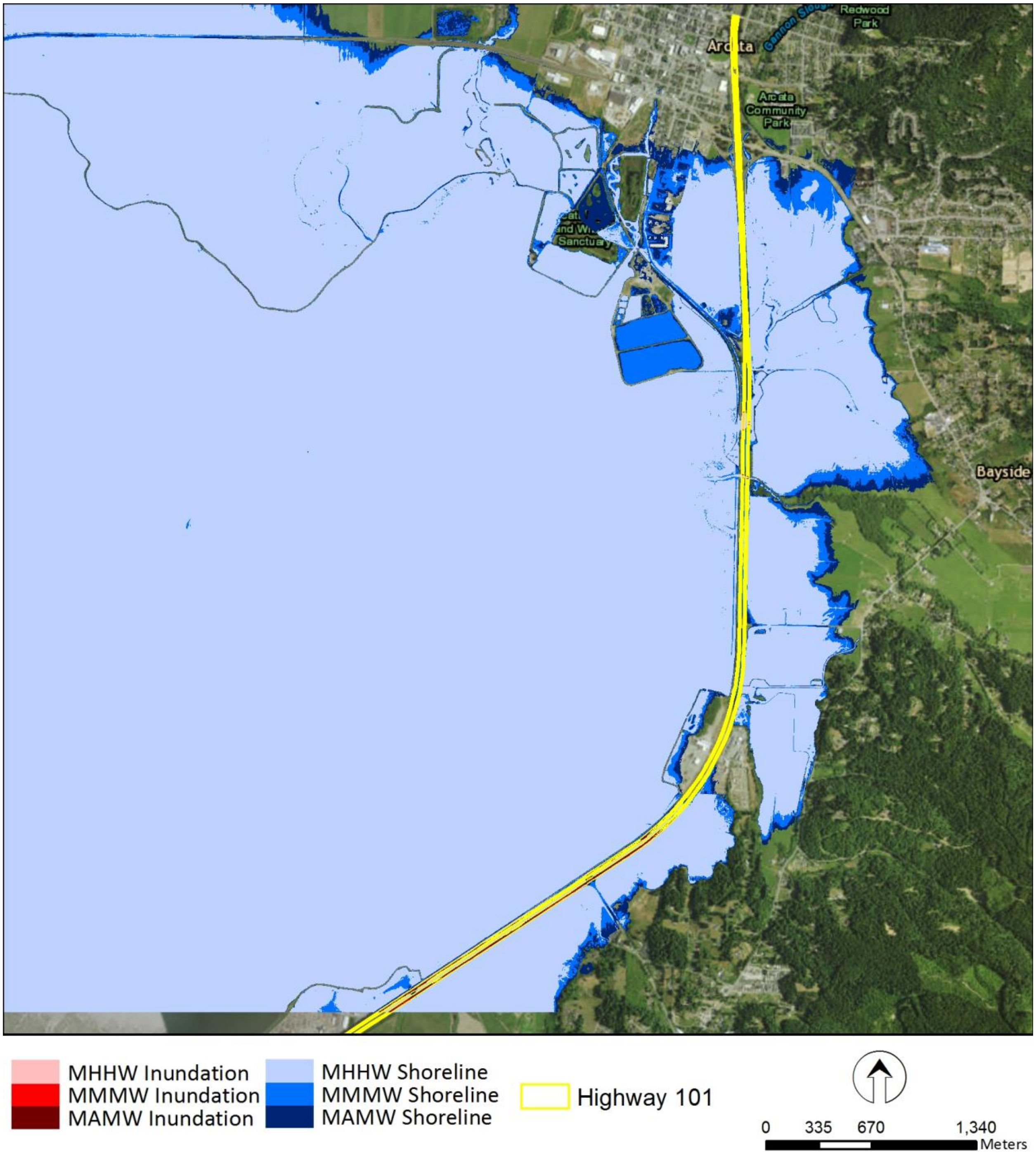

Figure 11: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

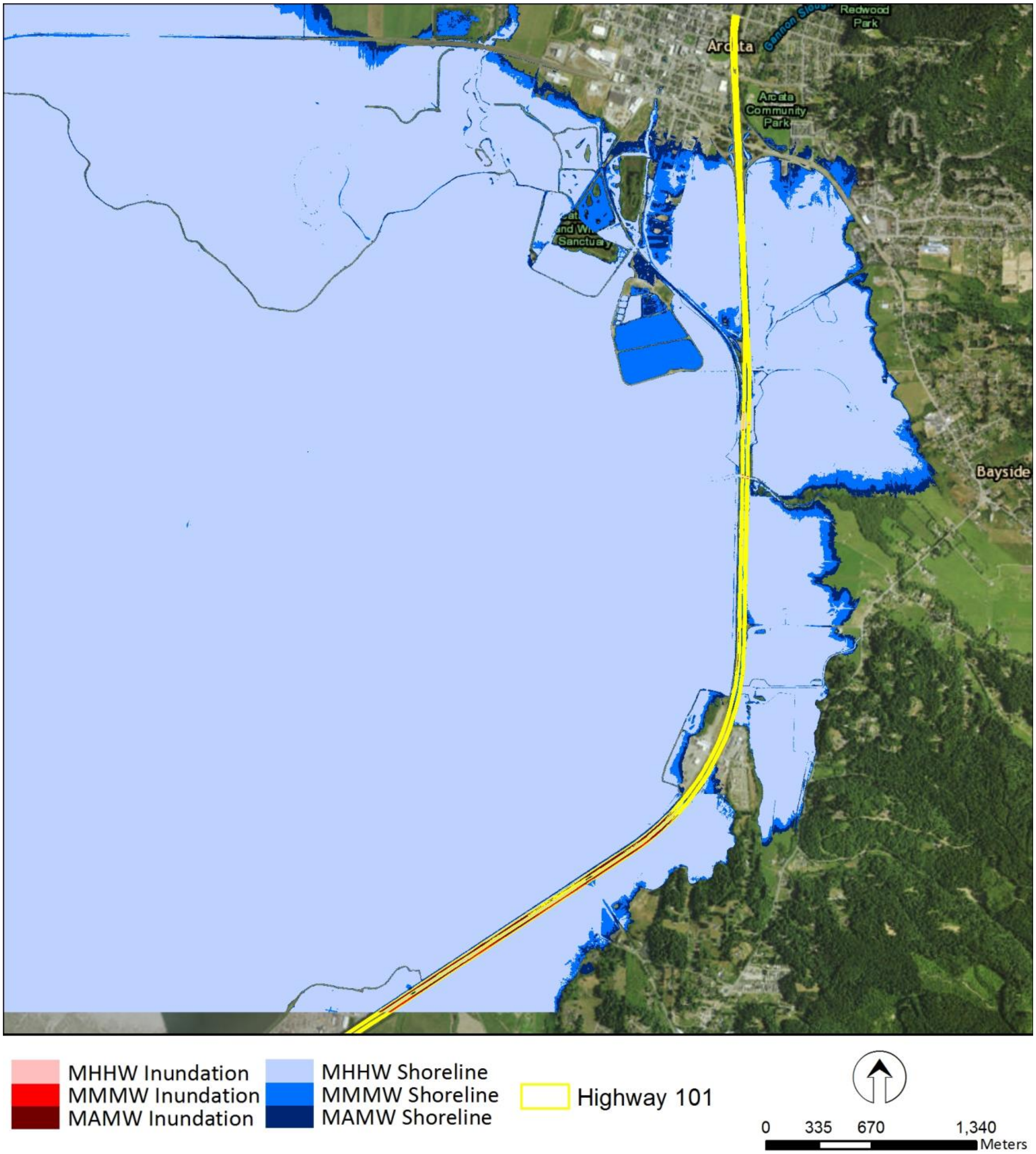

Figure 12: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection POI:

This section has been zoomed in to the area of flooding for clarity.

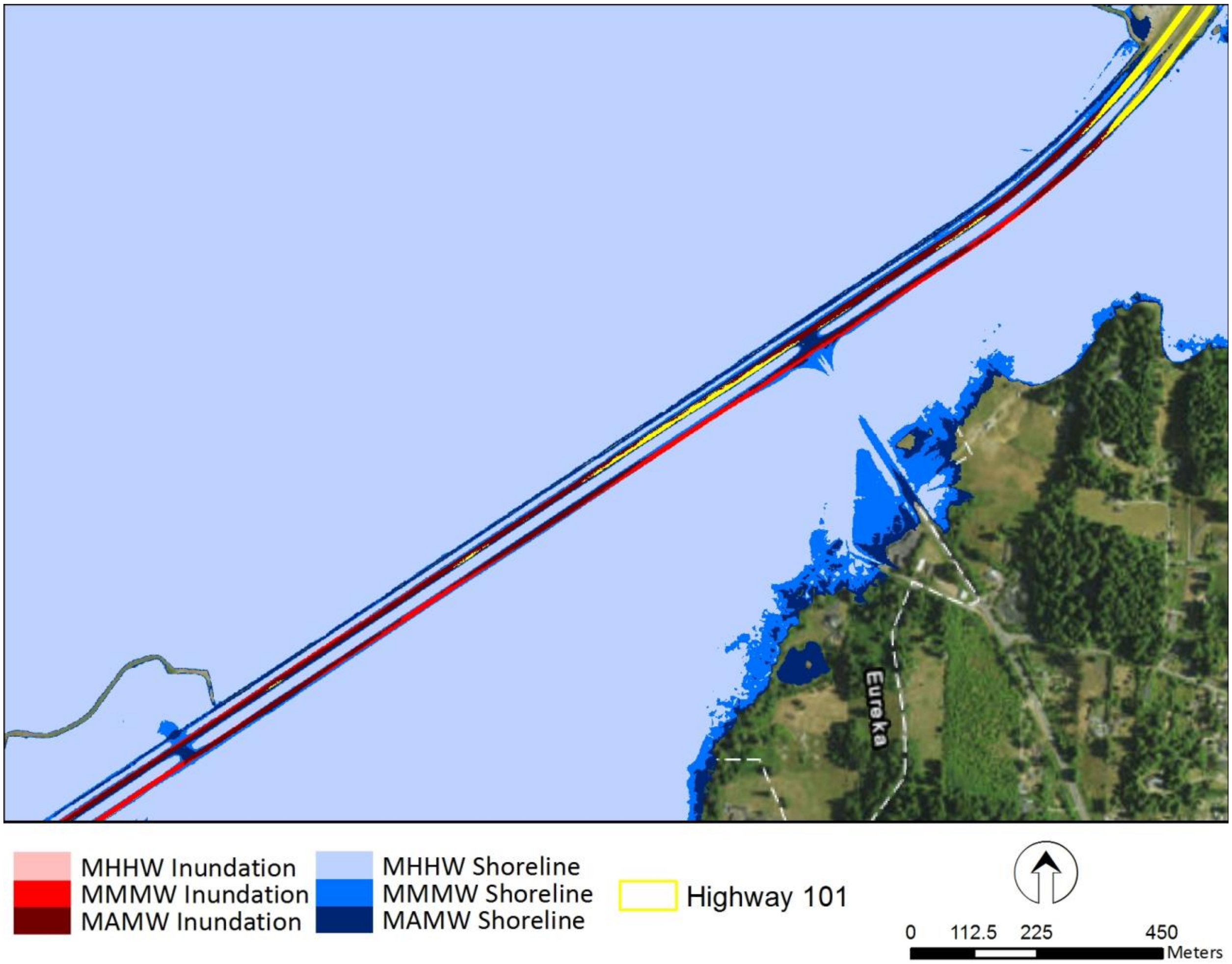

Figure 13: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Highway Section Eureka Slough to Brainard:

2030 Mid Sea Level Rise Projection:

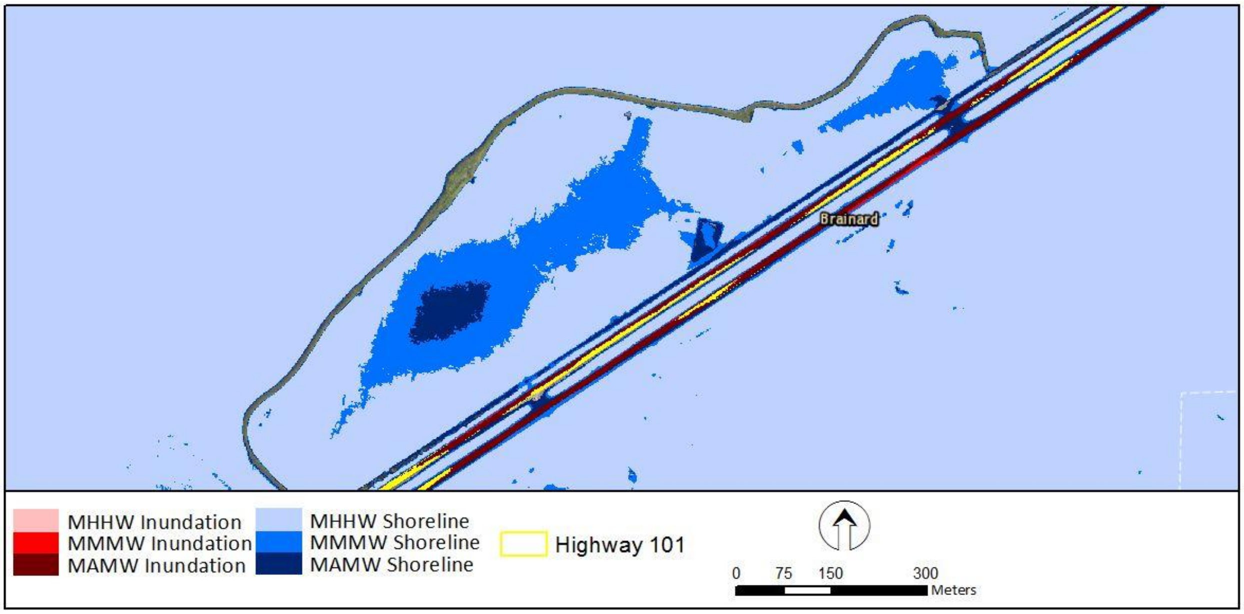

Figure 14: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

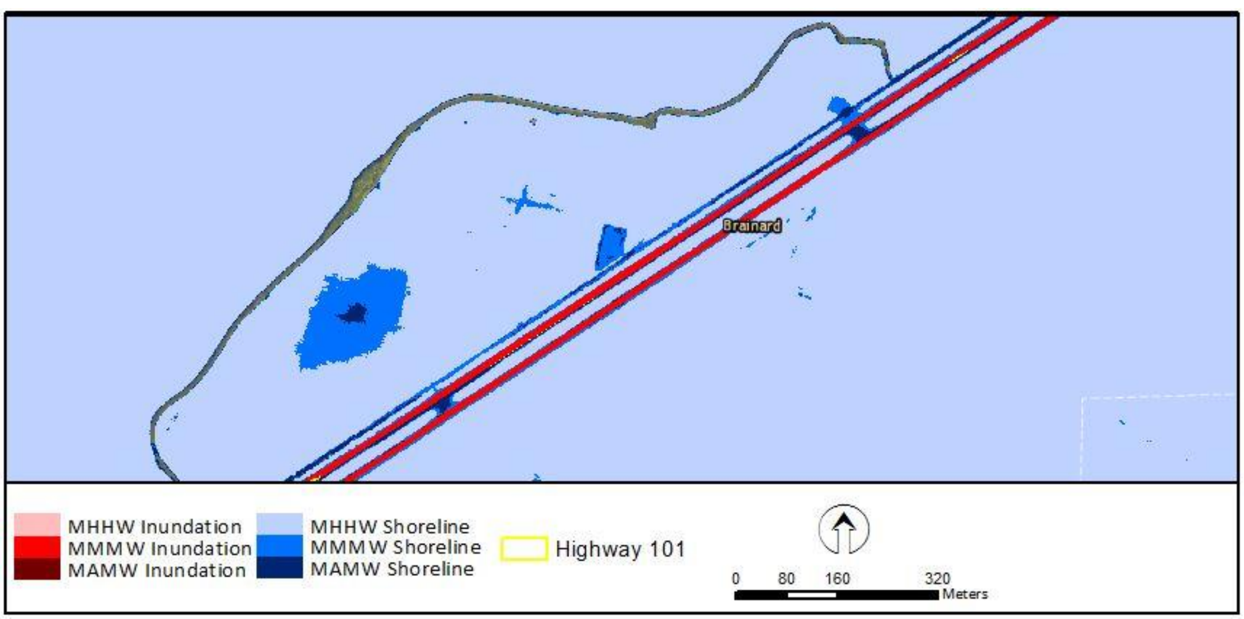

Figure 15: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Highway Section Eureka Slough:

2030 Mid Sea Level Rise Projection:

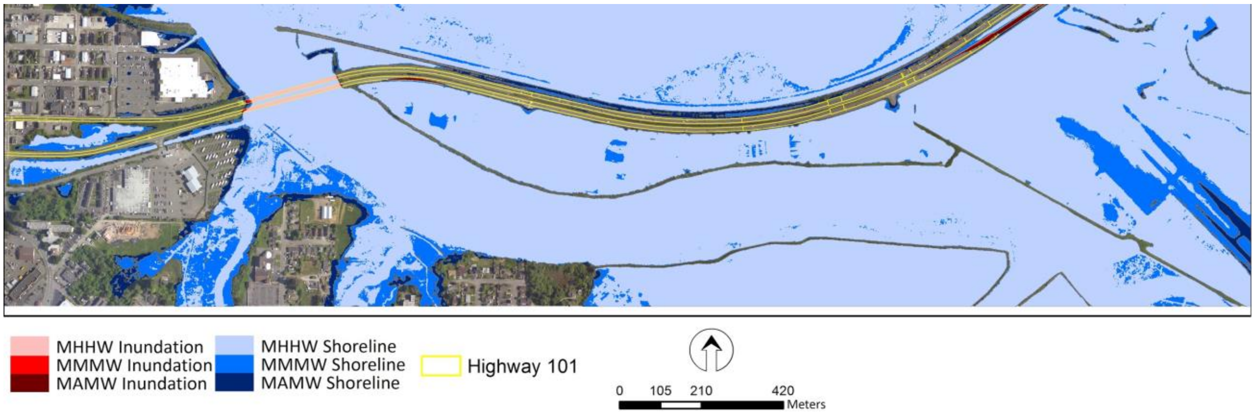

Figure 16: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

Figure 14: Map showing inundation for: (MHHW/ MMMW/ MAMW).

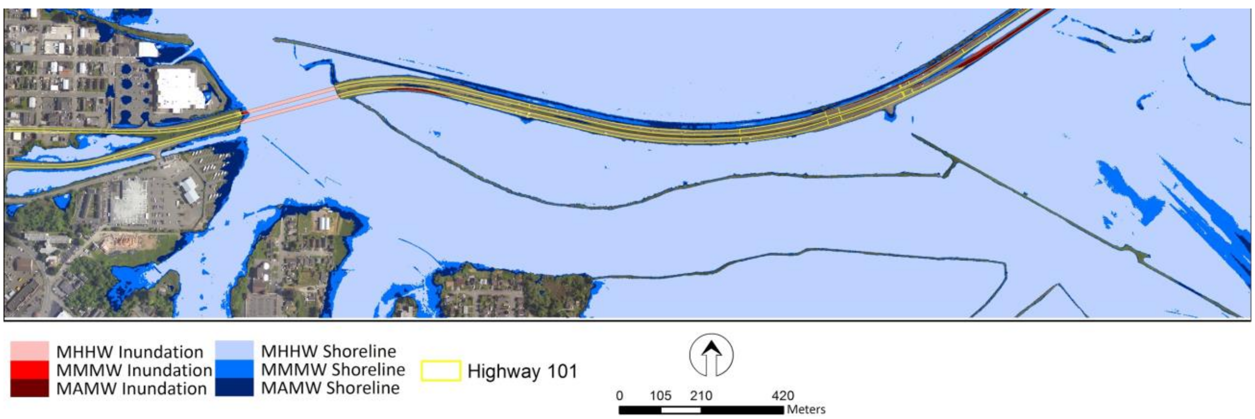

Figure 17: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Highway Section King Salmon to Hookton Slough POI:

2030 Mid Sea Level Rise Projection:

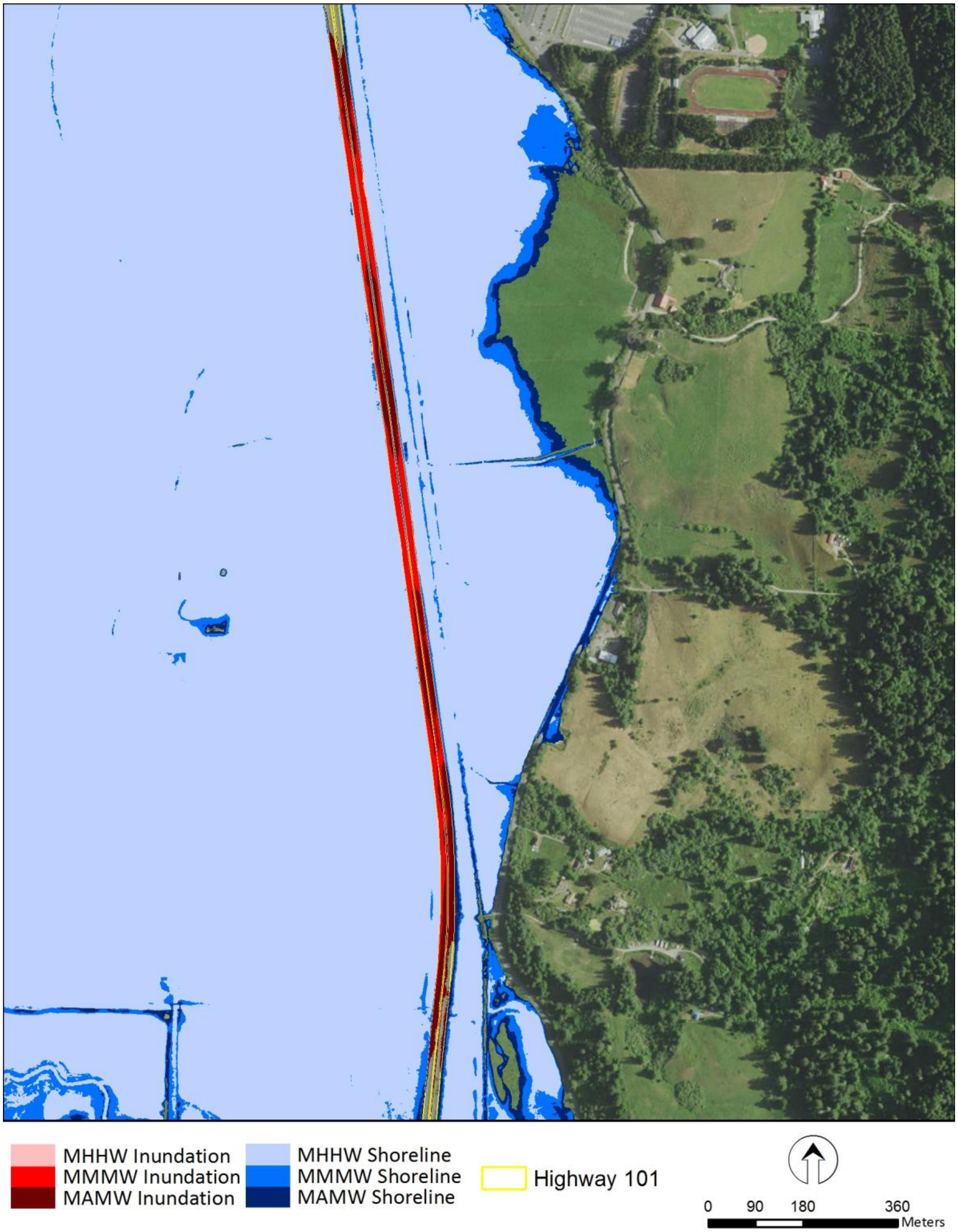

Figure 18: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection POI:

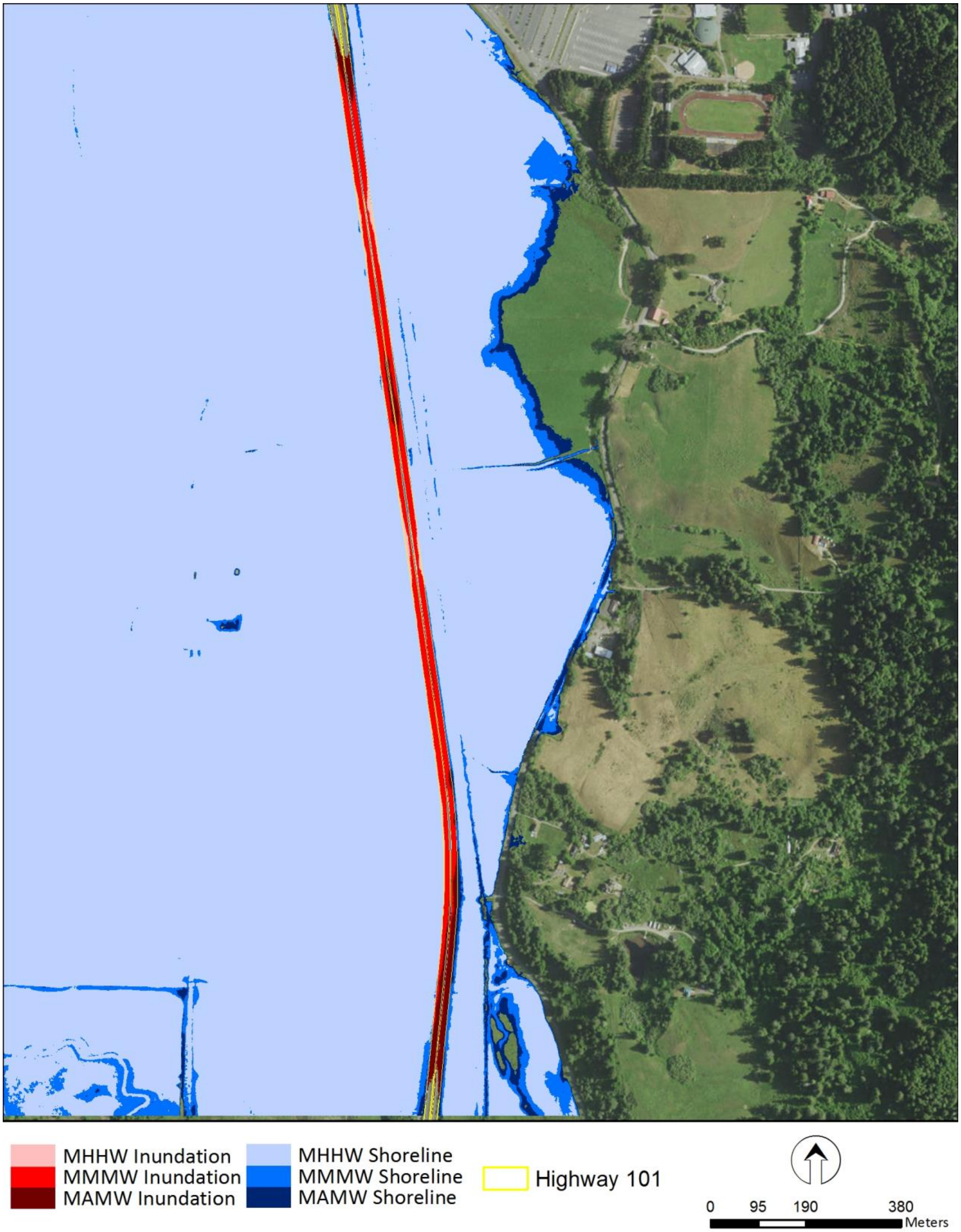

Figure 19: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Discussion of Results

The results below covered four study areas along the US 101 Highway.

1) Highway Section Arcata Eureka Corridor
2) Highway Section Eureka Slough to Brainard
3) Highway Section Eureka Slough
4) Highway Section King Salmon to Hookton Slough

The areas studied encompassed tidal projections for the years 2030 and 2050. Within these study areas three SLR scenarios low, medium and high were studied for three projected tidal frequencies MAMW, MHHW, and MMMW. For the results section, only Mid projections are displayed due to the number of scenario projections in this study being too large to be presented comprehensively in the report text. Full results can be found in appendix 1.

Daily Flooding Events 2030

Daily flooding was predicted in several regions of U.S. Highway 101 for the 2030 planning horizon. Daily flooding events were predicted to occur at the the Mean Higher High Water (MHHW) line. We took the average of our three sea level rise projections in order to show the average impacts experienced over all study areas. The area that experienced the most daily flooding was Eureka Slough (ES). Flooding that occurs on a daily basis potentially can cover 4% of the active highway surface adjacent to ES. The projected flooding has the potential to disrupt traffic flows and cause highway closures due to puddling and road bed degradation.

Projections for daily flooding also occurred in the following sections: Brainard to Arcata (BA), King Salmon to Hookton Slough (KSH), and from Eureka Slough to Brainard (ESB). For these sections, the approximate area that would be flooded on a daily basis is one percent of the active roadway. This value would pose little threat to disrupting the flow of traffic, but has the potential to undermine, or gradually damage the roadway, by slowly eroding base sediments.

Daily Flooding Events 2050

The predicted amount of land affected by daily flooding increases as expected for the 2050 planning horizon. We see KSH and ESB both experience approximately 6% of the active roadway being flooded on a daily basis. The amount of flooding that could occur on a daily basis will potentially cause traffic disruptions by halting traffic flows to allow tidal waters to recede, due to daily tidal patterns. Another impact that could be seen is the undermining of the roadway by the encroachment of tidal waters. Tidal waters potentially could reach these sections of highway during normal and daily tidal cycles.

The next section that will be impacted the most is ES. Here we saw that approximately 4.5% of the roadway will be flooded on a daily basis. The amount of flooding that will occur on a daily basis will potentially cause traffic disruptions, halting traffic flows to allow tidal waters to recede, due to daily tidal patterns. Another impact that will be seen is the undermining of the roadway due to the tidal waters that will be reaching these sections of highway during normal tidal cycles. BA will be affected the least by daily flooding. This section sees approximately 2% of the roadway being flooded on a daily basis. This would likely not cause traffic disruption but the small amount of flooding will begin to degrade the roadway from the saltwater intrusion and erosion.

Monthly Flooding Events 2030

All of our study areas saw projected monthly flooding from the Mean Monthly Maximum Water (MMMW) events for the 2030 planning horizon, when we averaged the total areas from the low, mid, and high projections. The total area that experienced these flooding events was roughly 27% of our total study area. Our analysis found that the least impacted area was the BA section, which experienced approximately 3% of its total area flooded in any given month.

The most impacted area under study was the KSH area, which saw approximately 10% of its total area flooded every month within our predictive model. This is a cause for concern as the safety corridor section of Highway 101 is the main transportation infrastructure connecting Humboldt Bay's two major cities, Eureka and Arcata - with projected flooding occurring in this region of the highway, logistical concerns for ground transportation need to be considered.

Monthly Flooding Events 2050

As expected, all of our areas under study see monthly flooding from MMMW for the averaged 2050 planning horizon. An interesting finding about these results is that they differ substantially from our 2030 findings. In 2050, our analysis found that the ES and BA sections were both tied for the least amount of monthly flooding at about 12% of total area flooded. The most impacted section under study was the ESB section which saw monthly flooding of approximately 50% of its total area, dwarfing the second most impacted area by 26%. Another interesting aspect of these results is that the ESB section saw more monthly flooding than any of the other sections' annual flooding when compared as a percentage.

Yearly Flooding Events 2030

The study area most affected by annual tidal events, or Mean Annual Maximum Water (MAMW), was ESB with inundation reaching approximately 78% during annual tidal events. This is a major cause for concern as the roadway would very likely be closed during the flood event. The second most affected section was KSH with annual flooding events causing approximately 24% of the roadway being inundated. The third most affected section was BA with annual flooding inundating approximately 15% of the section followed by ES with annual flooding events covering approximately 12% of the roadway.

This would suggest yearly flooding events in ESB and KS as the most vulnerable areas to MAMW flooding events. This would suggest instances of flooding along US Highway 101 and the safety corridor during these annual high tide events which could result in intermittent to potentially long-term closures during these yearly flood events.

Yearly Flooding Events 2050

The study areas most affected by projected annual tidal (MAMW) events in 2050 was ESB with an average value of approximately 96% during annual tidal events. The second area affected was KSH which had an average approximate increase of 30% during projected annual high tide events. The third most affected area was BA which had tidal event increases of approximately 27% followed by ES which measured 25% during MAMW events. This would suggest that instances of flooding along US Highway 101 and the safety corridor during these annual high tide events could result in severe inundation and closing of the highway in all four study areas. Potential impacts to the roadway would be the undermining of the foundation and the erosion of base sediments due to repeated wave energy and related soil leaching during these tidal events which could potentially render the highway unusable if no changes are made to the highway from its current state.

As discussed above, these estimates are for the mid-range SLR scenario. It should be noted that even in the low-range SLR scenario, our study region is expected to undergo at least some inundation annually. Under the high SLR scenario, road closures on the 101 corridor could become a near-daily part of life in our local region by 2030.

Conclusion

Our analysis looked at the projected tidal flooding events that would occur on the 2030, and 2050 planning horizons. These tidal events due to sea level rise will eventually influence the flow of traffic on U.S. Highway 101 with flooding and repeated disruption to traffic flows along Humboldt Bay's most important traffic corridor.

These findings are significant when considering that Humboldt County is a remote location, with Highway 101 being the only major transportation infrastructure through the entire county. The closure of the traffic corridor between Arcata and Eureka would be a major disruption to the local economy; this section of the highway is heavily travelled by thousands of people on a daily basis. Couple this with the fact that Humboldt roads and bridges are currently in a weakened state, it becomes apparent why the vulnerability of these systems need to be a key planning focus for future developments. Sea level rise should not be ignored when making long term infrastructure installations. By taking into account sea level rise measurements and predictions, infrastructure can be designed to withstand tidal waters, and/or be redesigned in a way to avoid future tidal impacts. Shoreline composition has the potential to change as more land will be exposed to salt water for longer periods of time; saltwater wetlands potentially could appear.

By being proactive in our sea level rise studies, we can predict and plan for rising seas. By utilizing models similar to those utilized in this study, we can predict the potential impacts associated with tidal flooding in order to plan our infrastructure in a way that will avoid damage from tidal waters. As time goes on, studies like this will become much more important. They will be the basis upon which coastal infrastructure will be planned, and determine the future of land uses in coastal areas. This allows communities and organizations to be more proactive with their planning, instead of reactive.

Further Study

Our study can be expanded upon further by utilizing hydrodynamic models to further look at the impacts that tidal flooding will have on the highway. This should also take into account the functionality of shoreline structures, such as dikes, levees, and tidal gauges as per their abilities to manage and control tidal waters. Highway 101 will not be the only roadway affected by SLR, and further study should be done to evaluate impacts to the rest of the bay's transportation infrastructure.

A further consideration for study would be to determine and define at what point the levels of inundation on the road surface would be severe enough to cause road closures. This could be done based on width and length measurements and of the road surface and topography of the corridor overall and based on safety limitations set by Caltrans.

Disclaimer of our Research

Our estimates are based on the Eureka, California 1/3 Arc-second NAVD 88 Coastal Digital Elevation Model. Additionally the predictive model was a bathtub model, a 2D non-dynamic virtual surface layer which doesn't account for wave action, associated hydrodynamics, storm surges, effects of wind, levee or dyke breaching. Our predictive models are for planning purposes only and should not be used for navigation, or permitting.

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Appendix 1 Maps

Highway Section Arcata Eureka Corridor:

2030 High Sea Level Rise Projection:

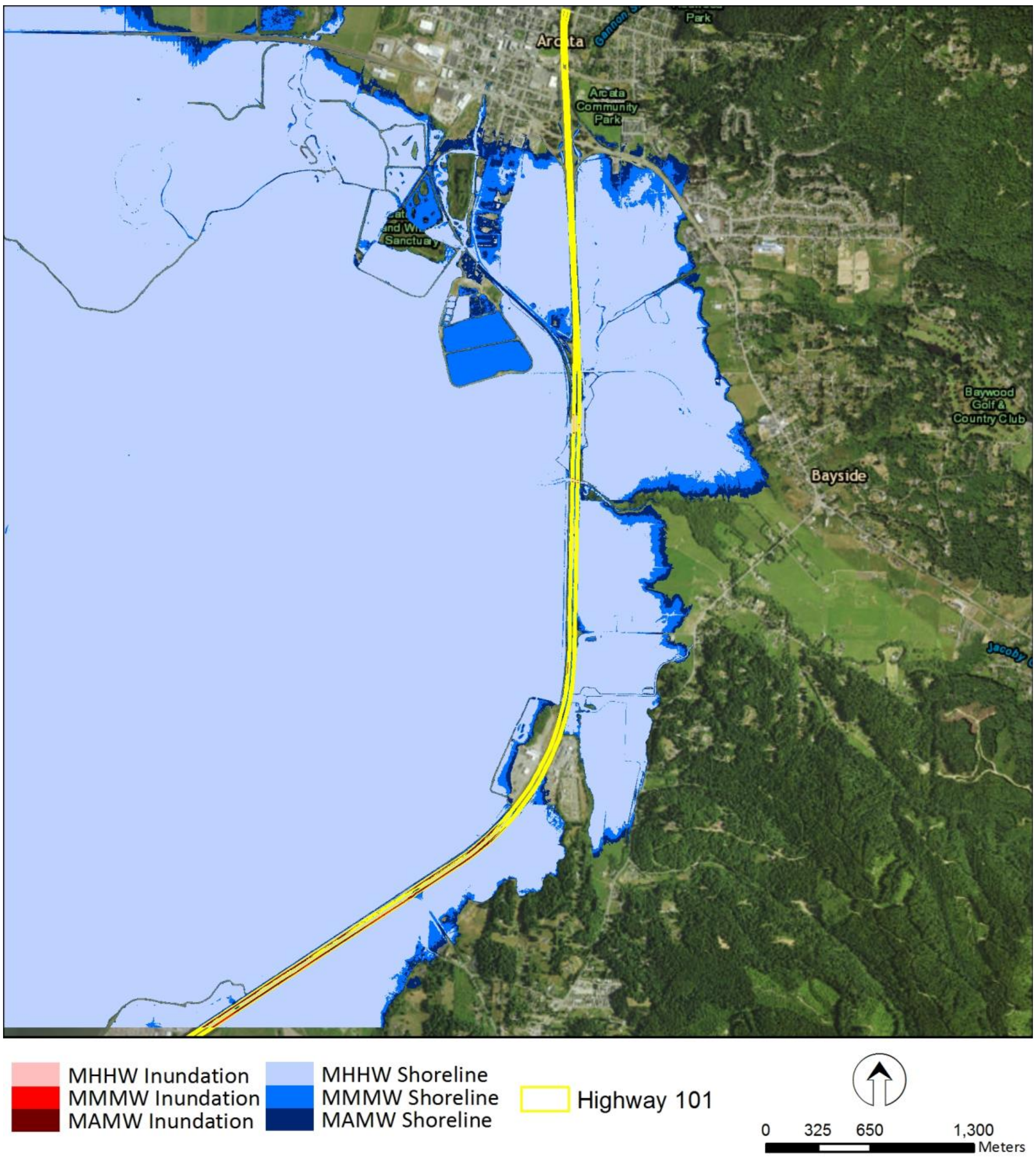


Figure 20: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Mid Sea Level Rise Projection:

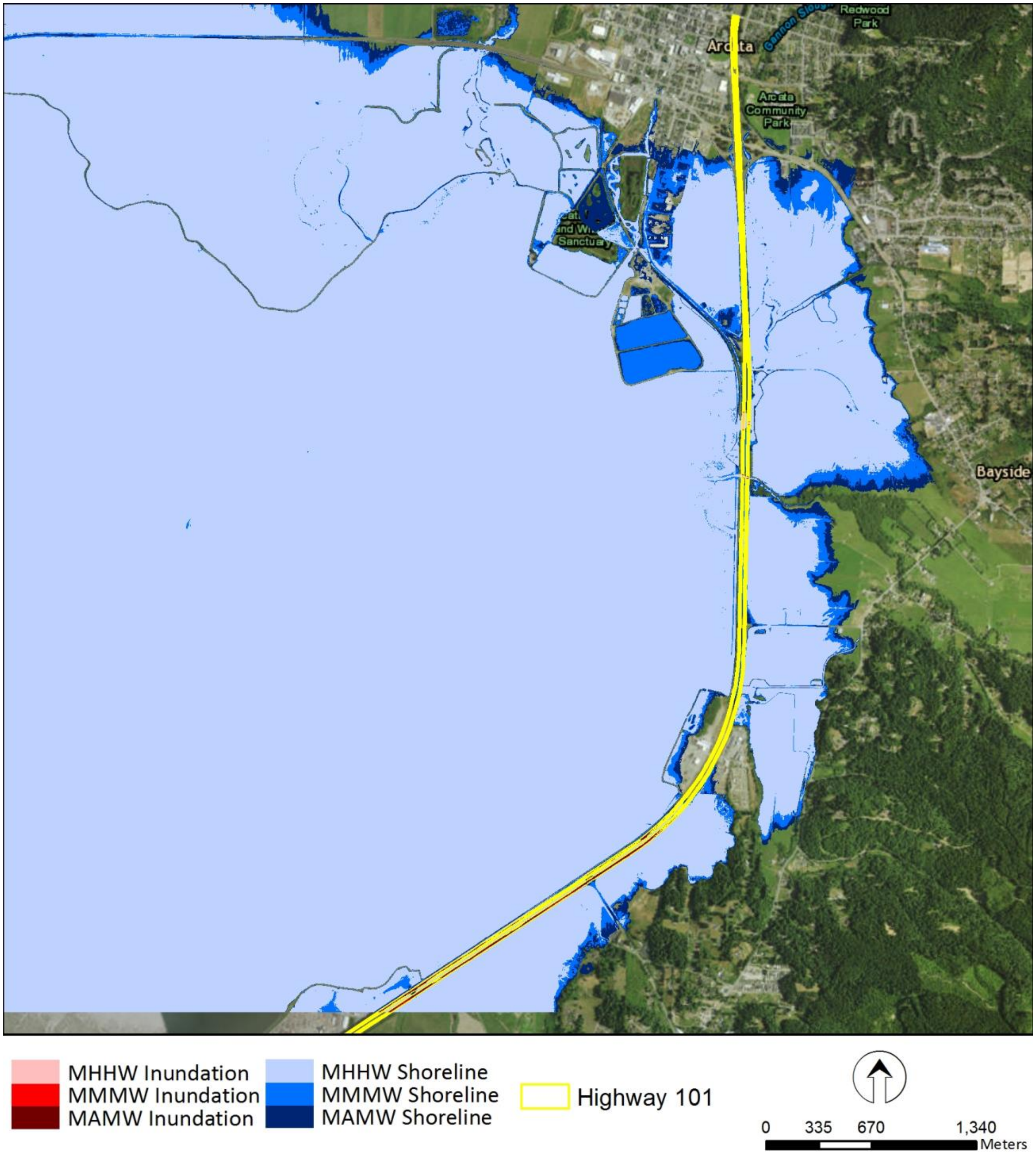


Figure 21: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Low Sea Level Rise Projection:

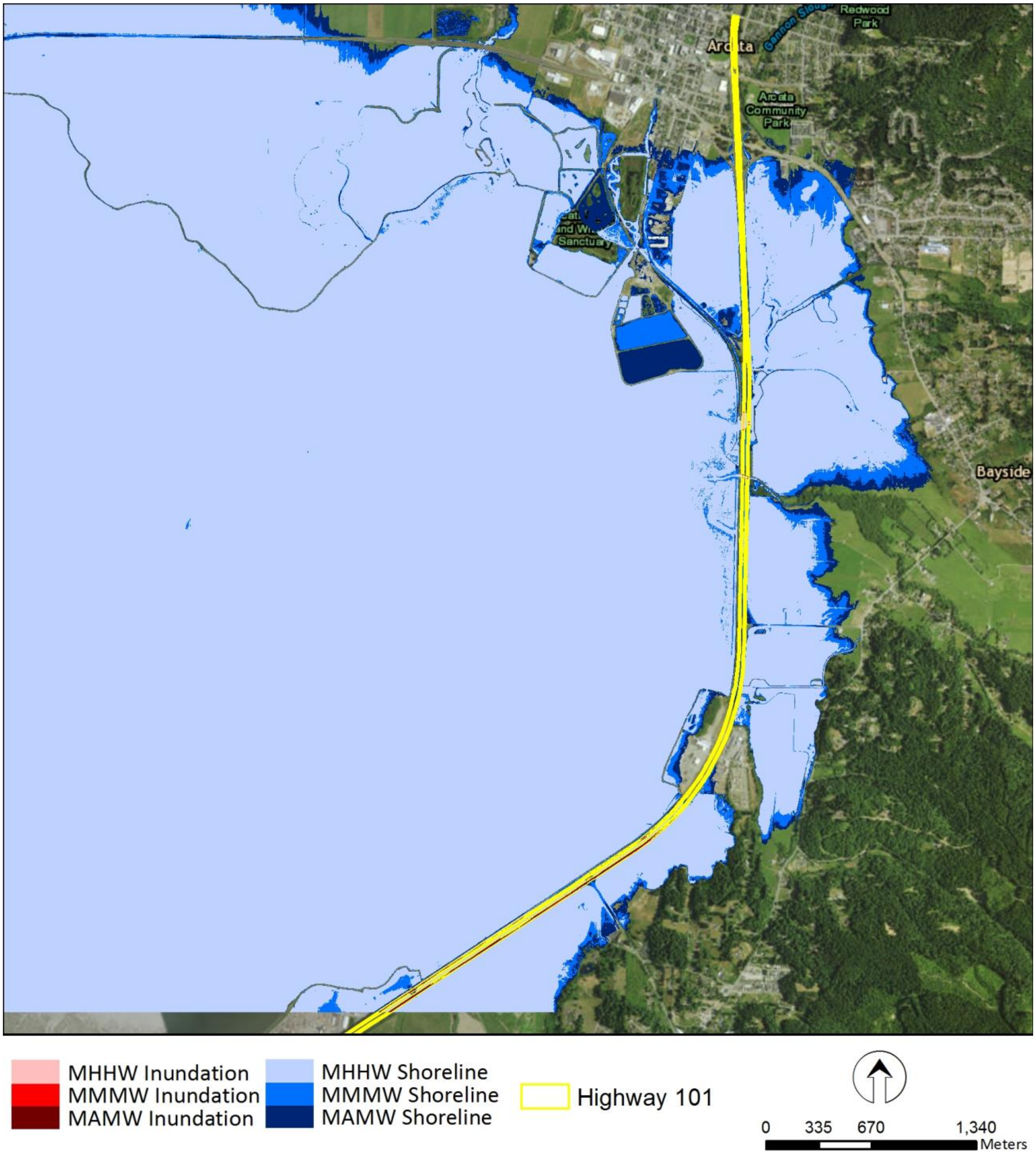


Figure 22: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 High Sea Level Rise Projection:

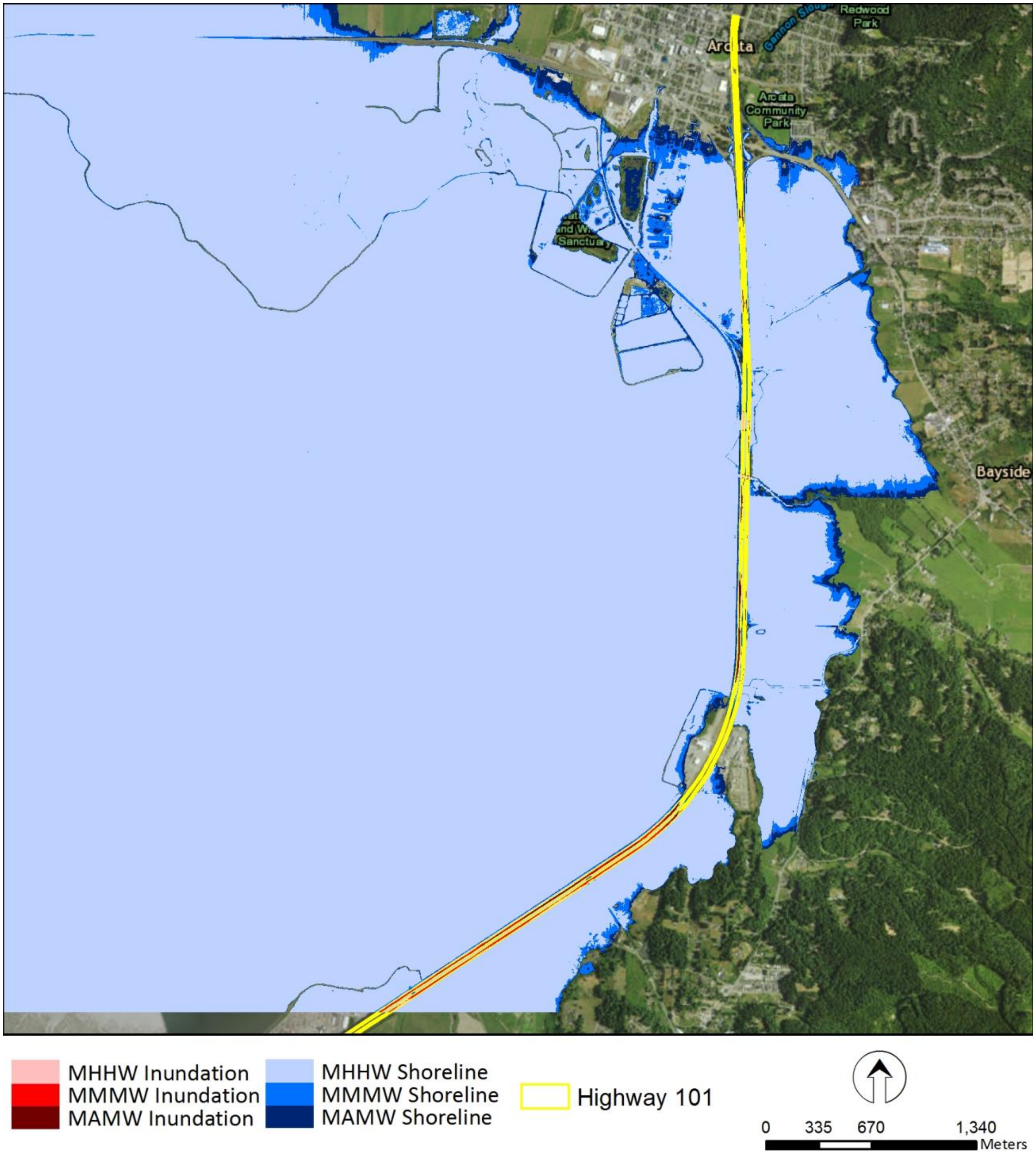


Figure 23: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

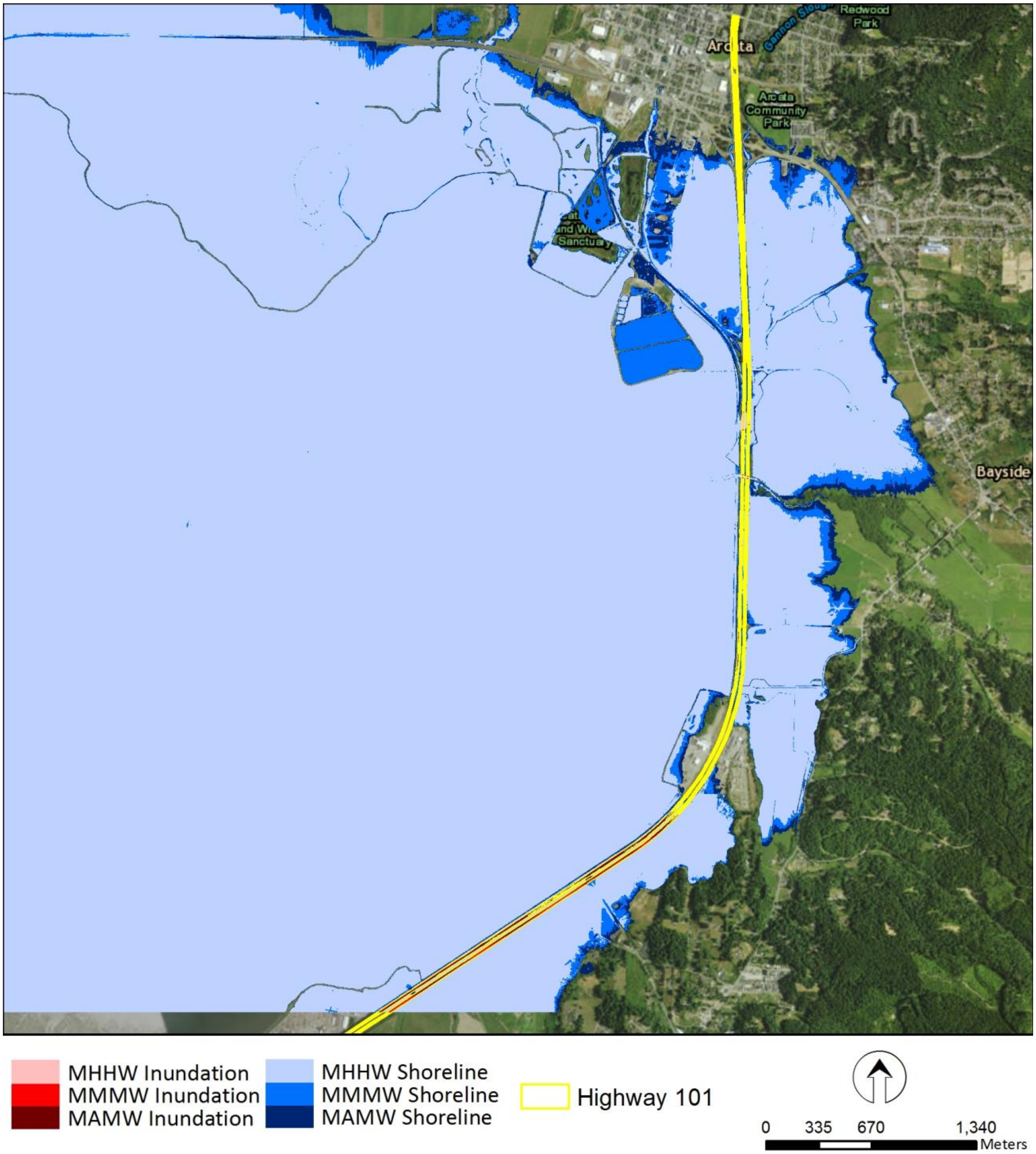


Figure 24: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Low Sea Level Rise Projection:

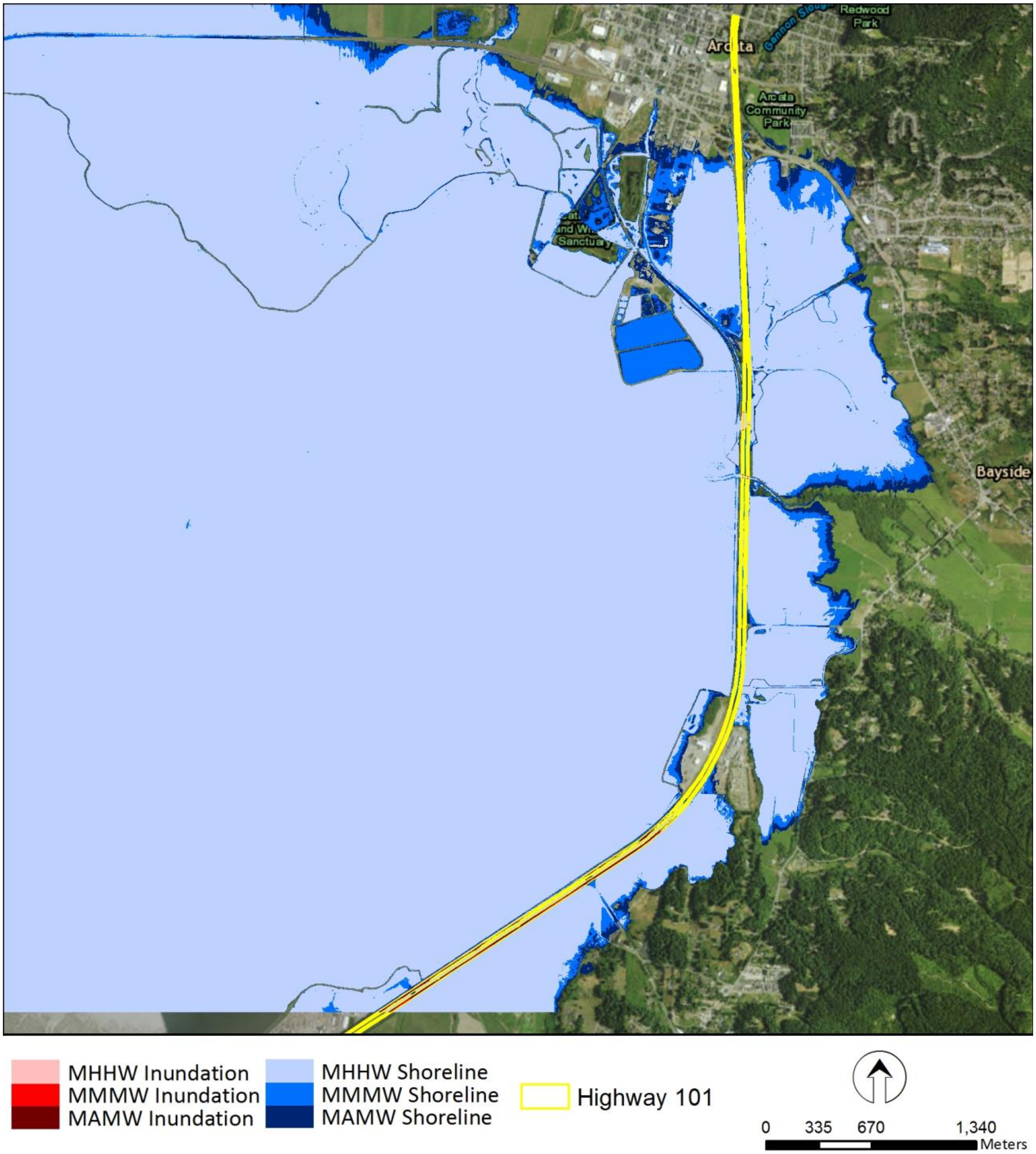


Figure 25: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection - POI:

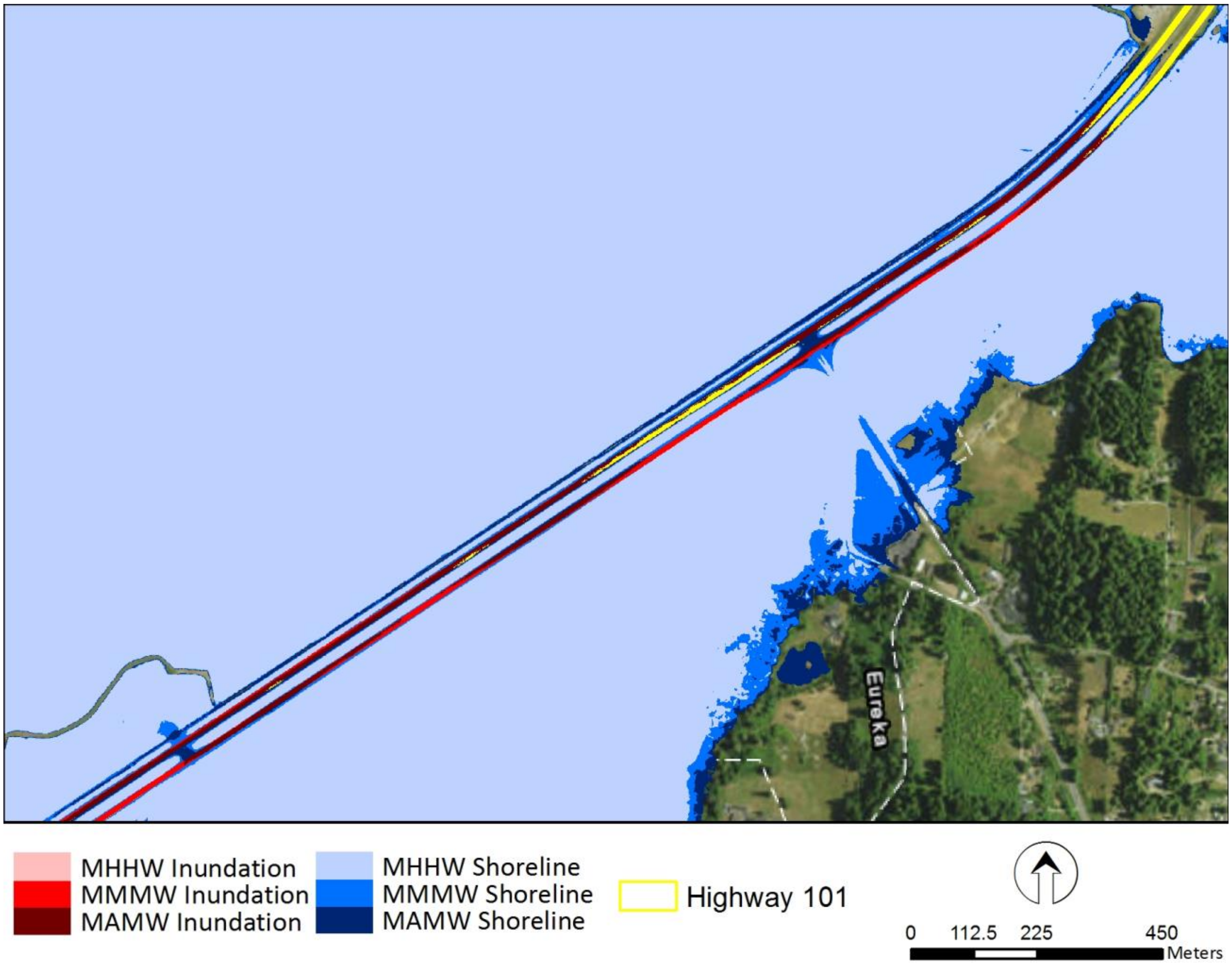


Figure 26: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Highway Section Eureka Slough to Brainard:

2030 Low Sea Level Rise Projection:

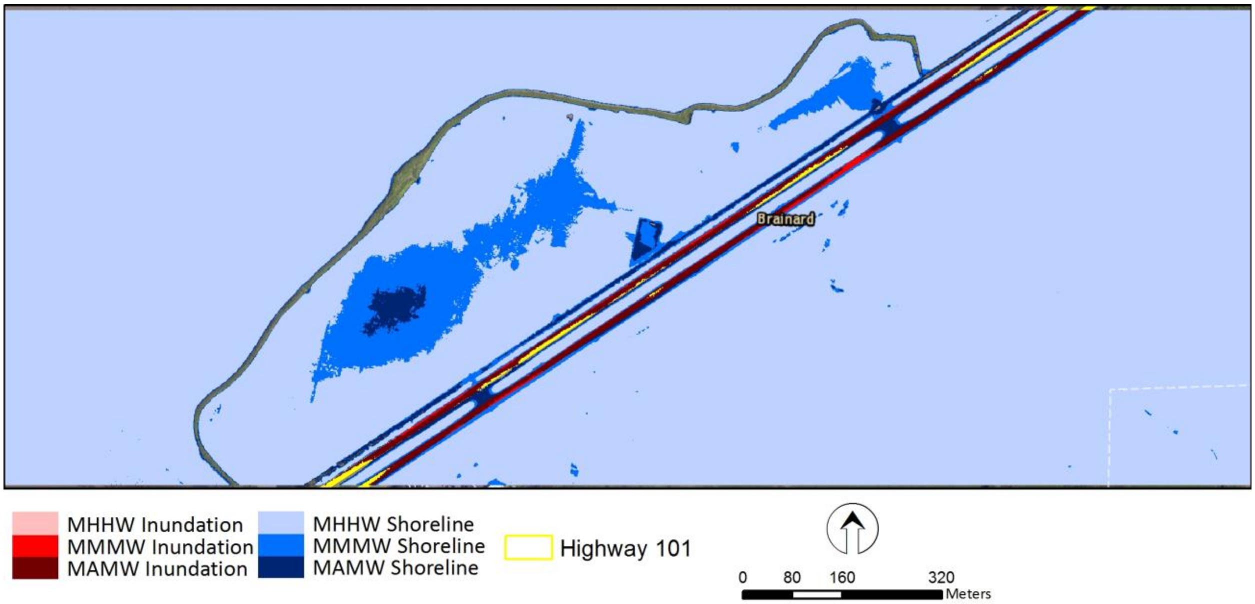


Figure 27: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Mid Sea Level Rise Projection:

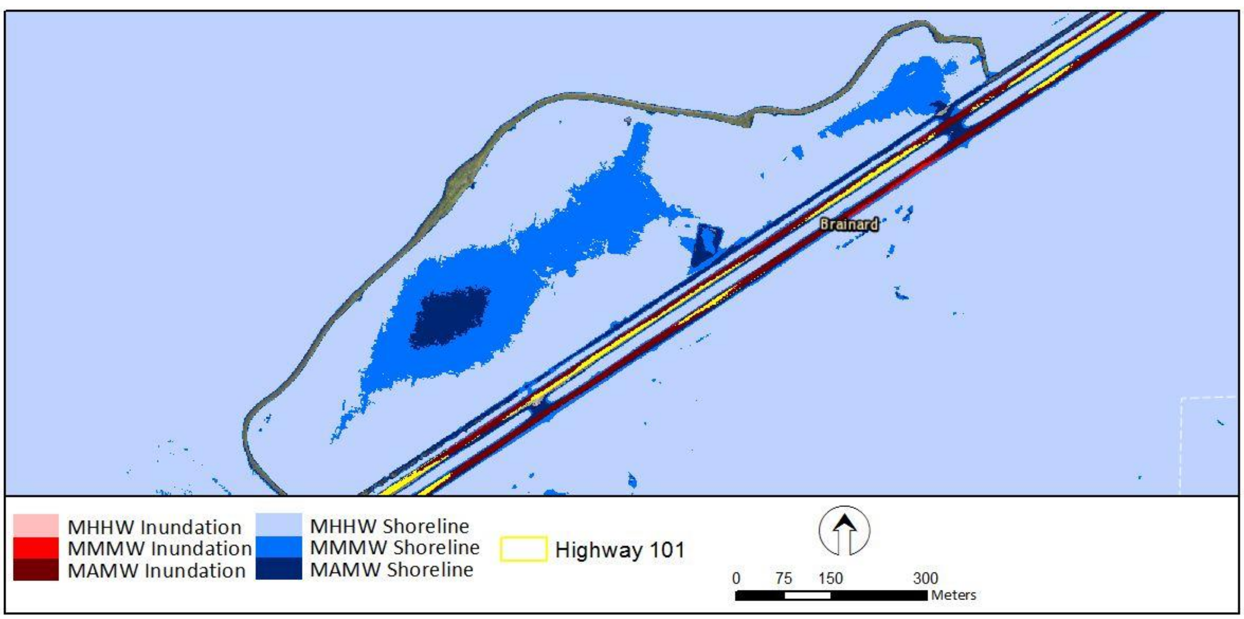


Figure 28: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 High Sea Level Rise Projections:

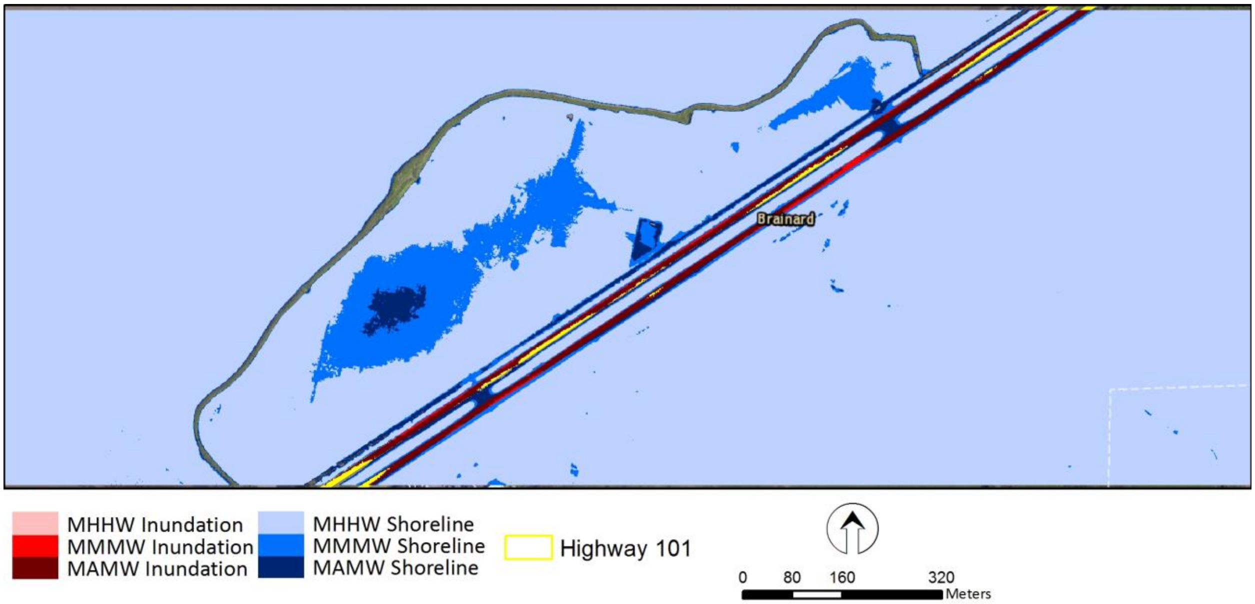


Figure 29: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Low Sea Level Rise Projection:

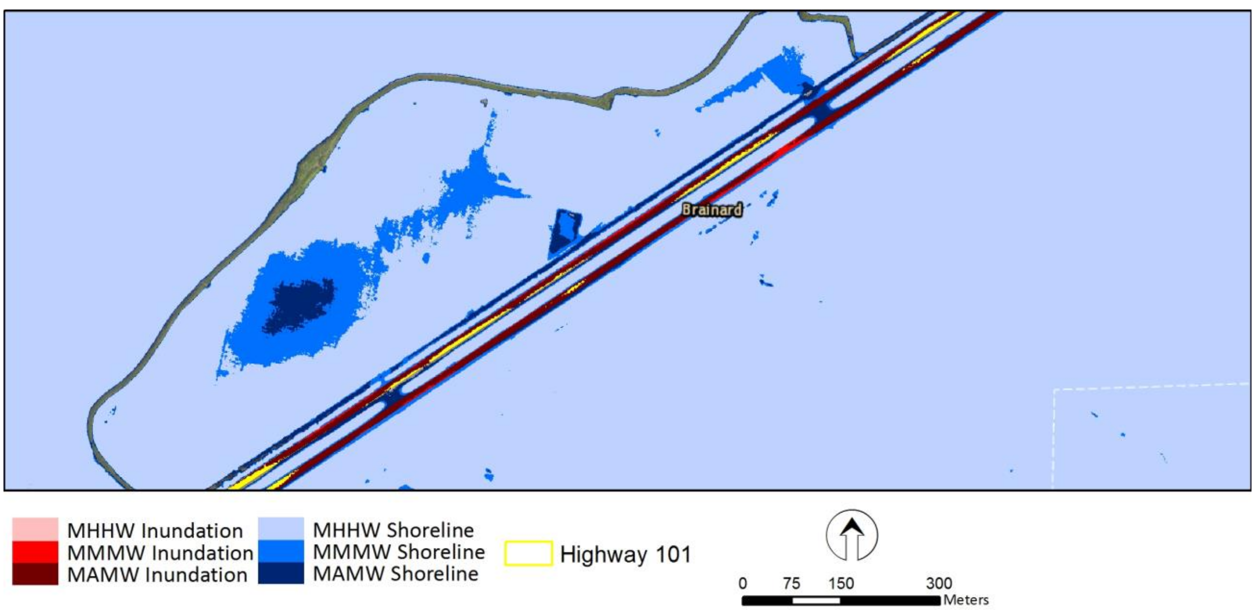


Figure 30: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

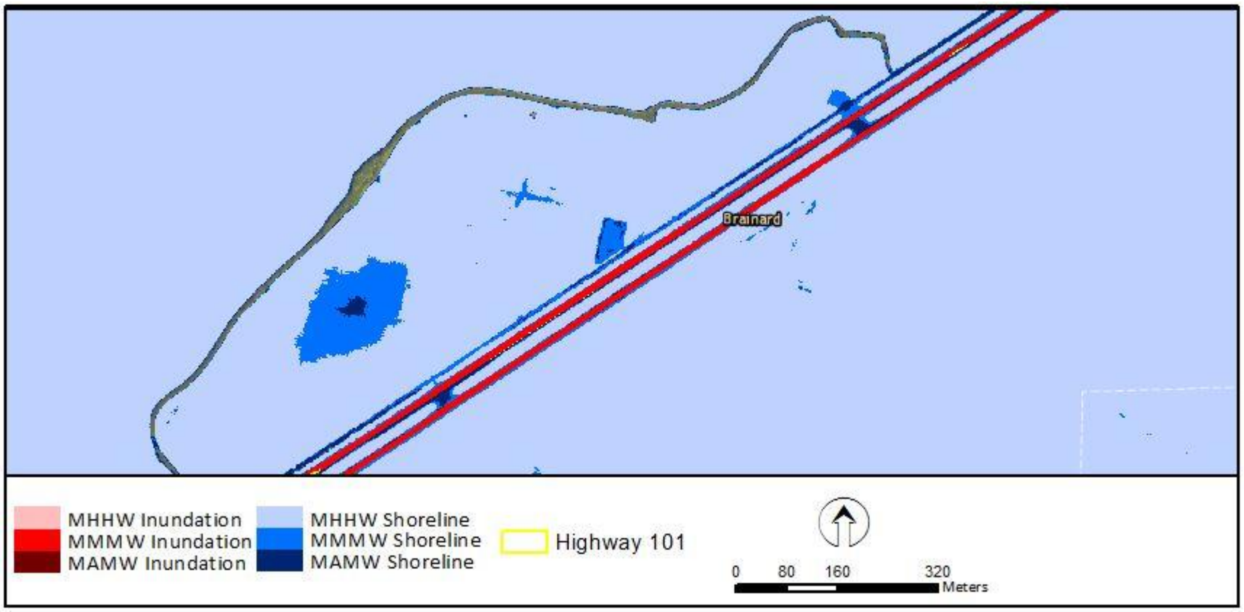


Figure 31: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 High Sea Level Projection:

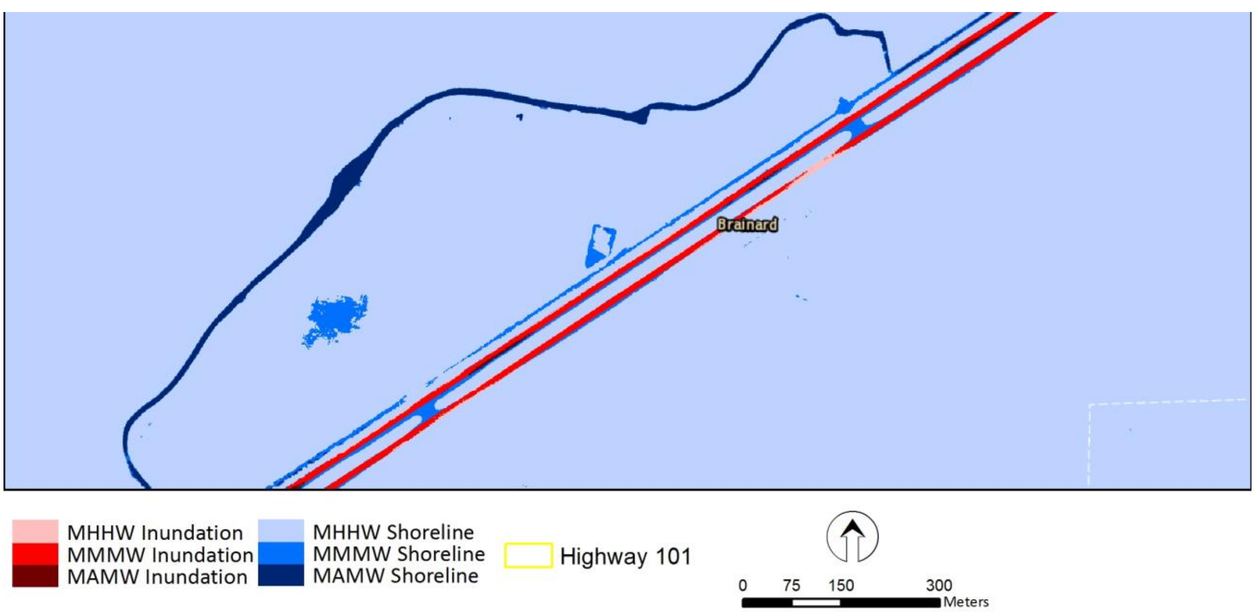


Figure 32: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Highway Section Eureka Slough:

2030 High Sea Level Rise Projection:

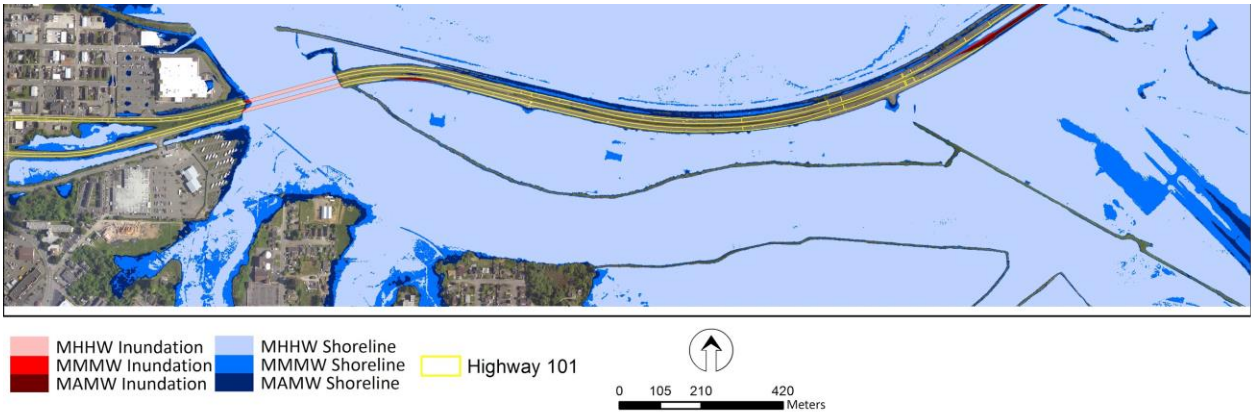


Figure 33: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Mid Sea Level Rise Projection:

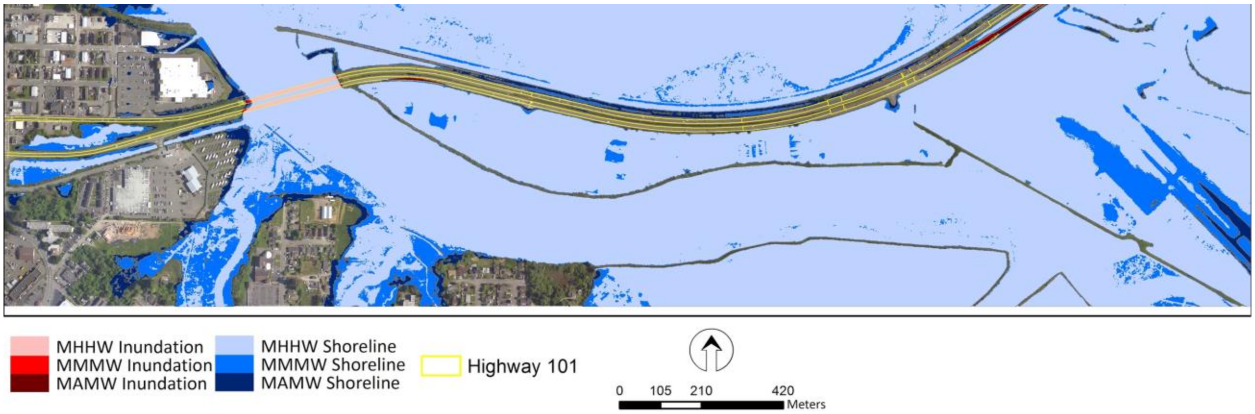


Figure 34: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Low Sea Level Rise Projection:

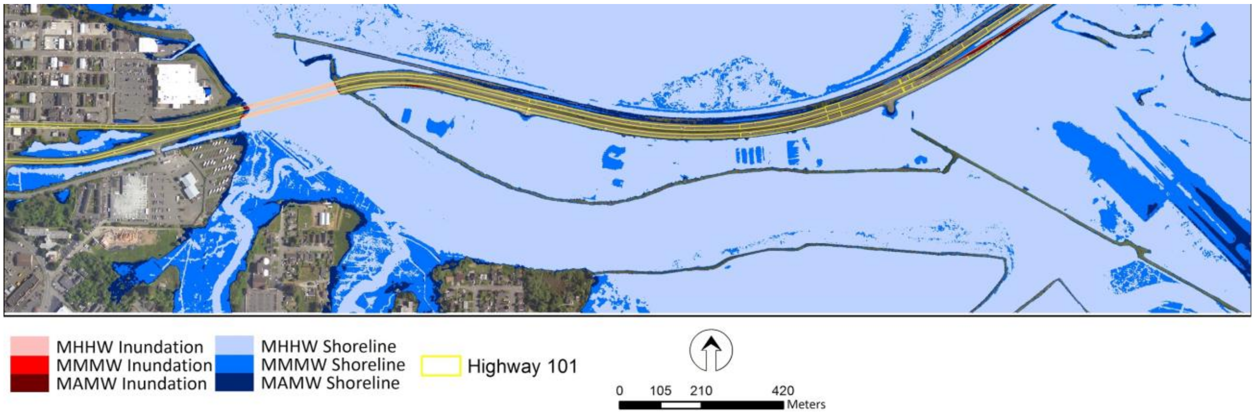


Figure 35: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 High Sea Level Rise Projection:

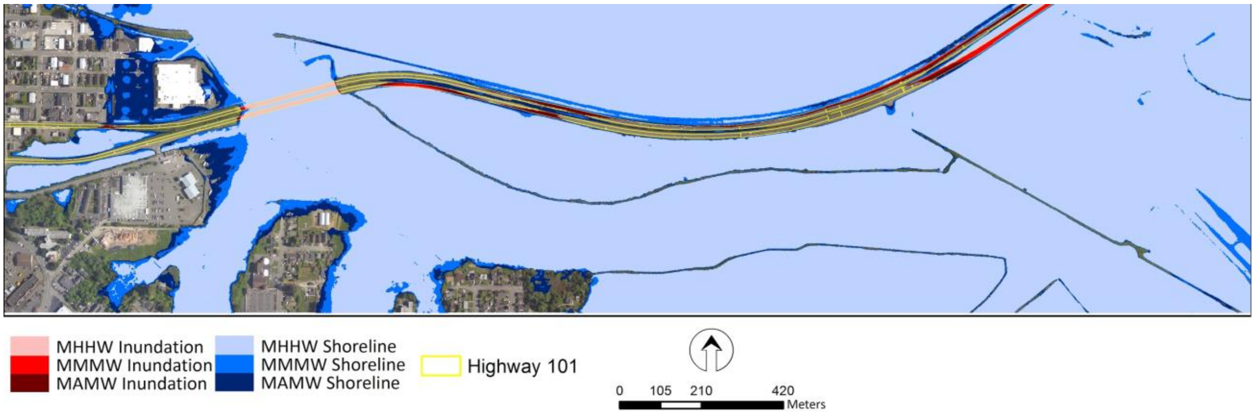


Figure 36: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

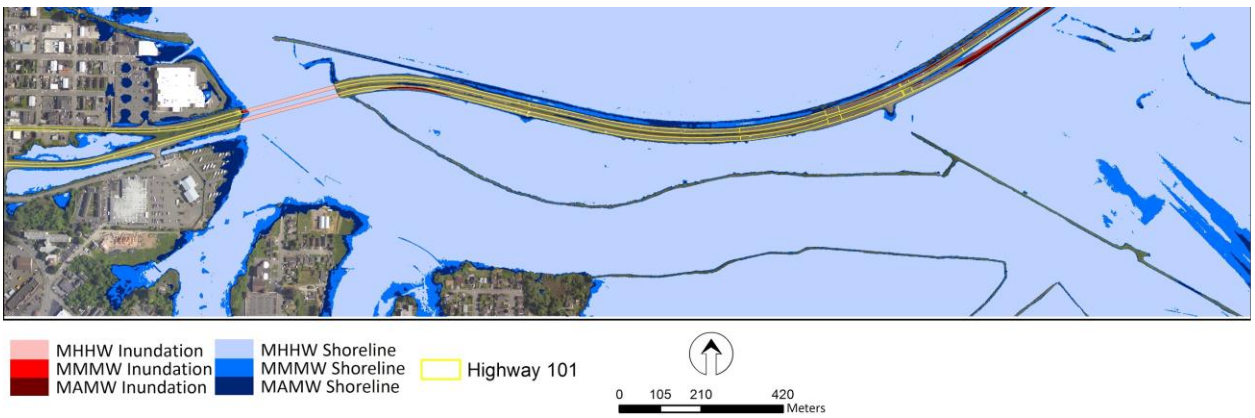


Figure 37: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Low Sea Level Rise Projection:

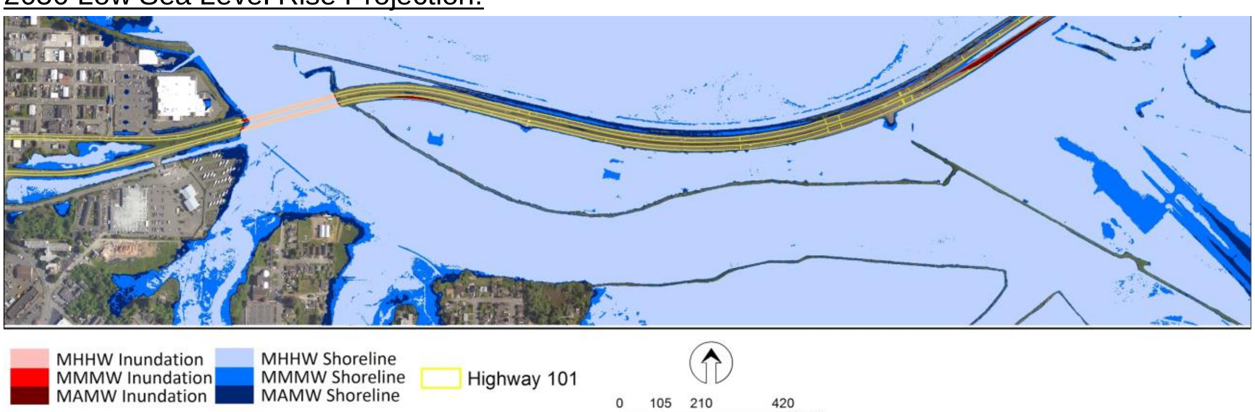


Figure 38: Map showing inundation for: (MHHW/ MMMW/ MAMW)

Highway Section King Salmon to Hookton Slough:

2030 High Sea Level Rise Projection:

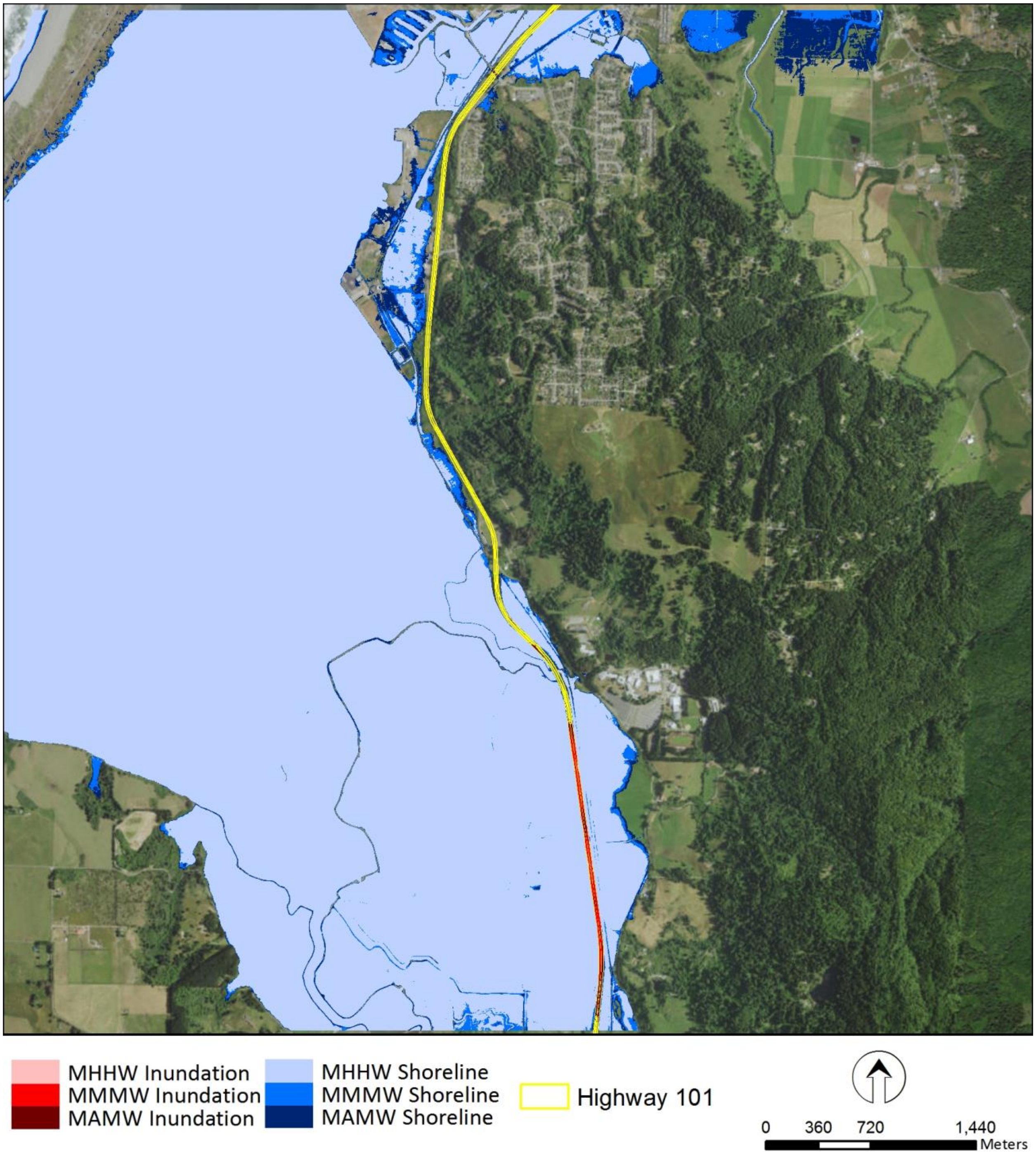


Figure 39: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Mid Sea Level Rise Projection:

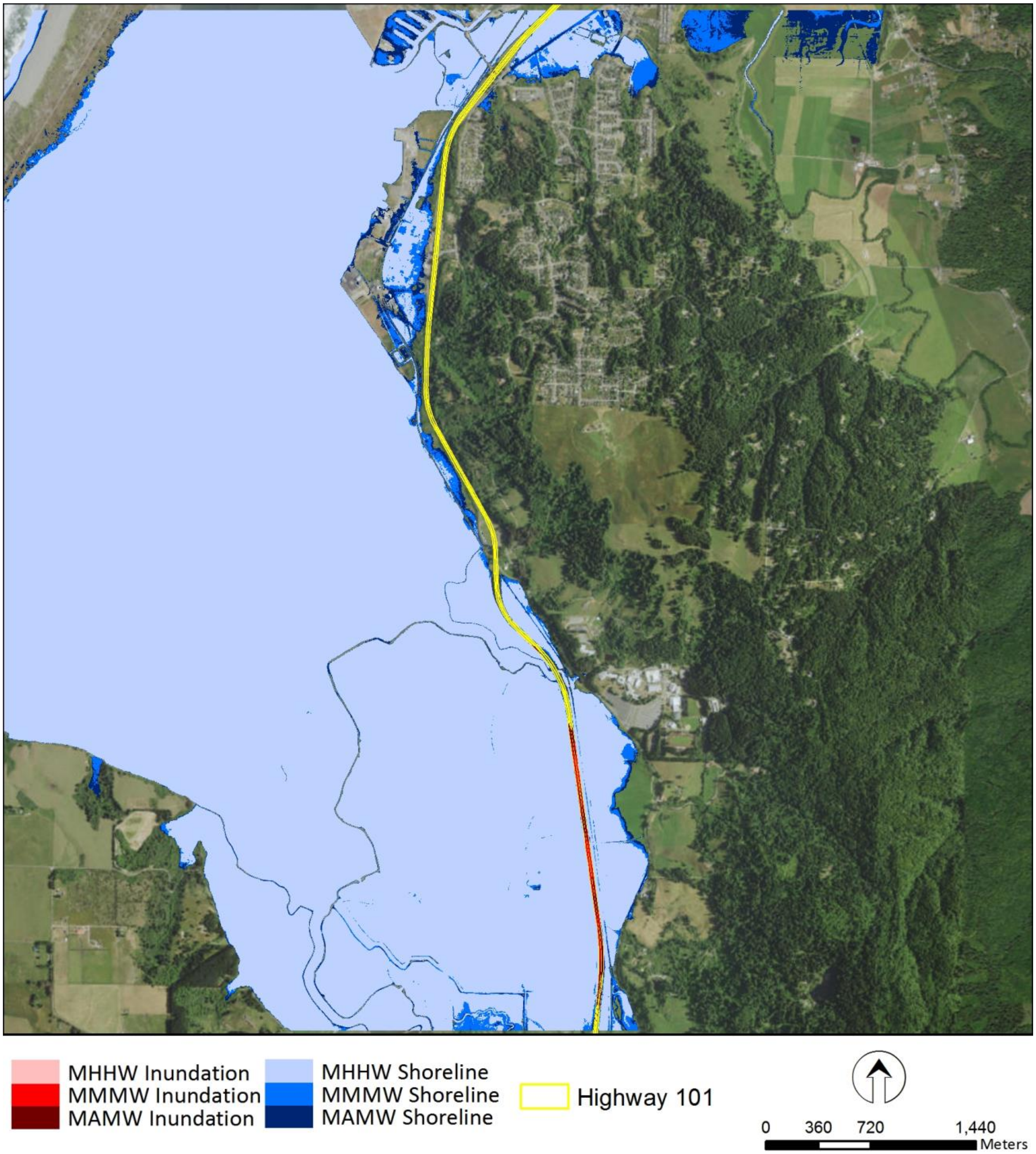


Figure 40: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Low Sea Level Rise Projection:

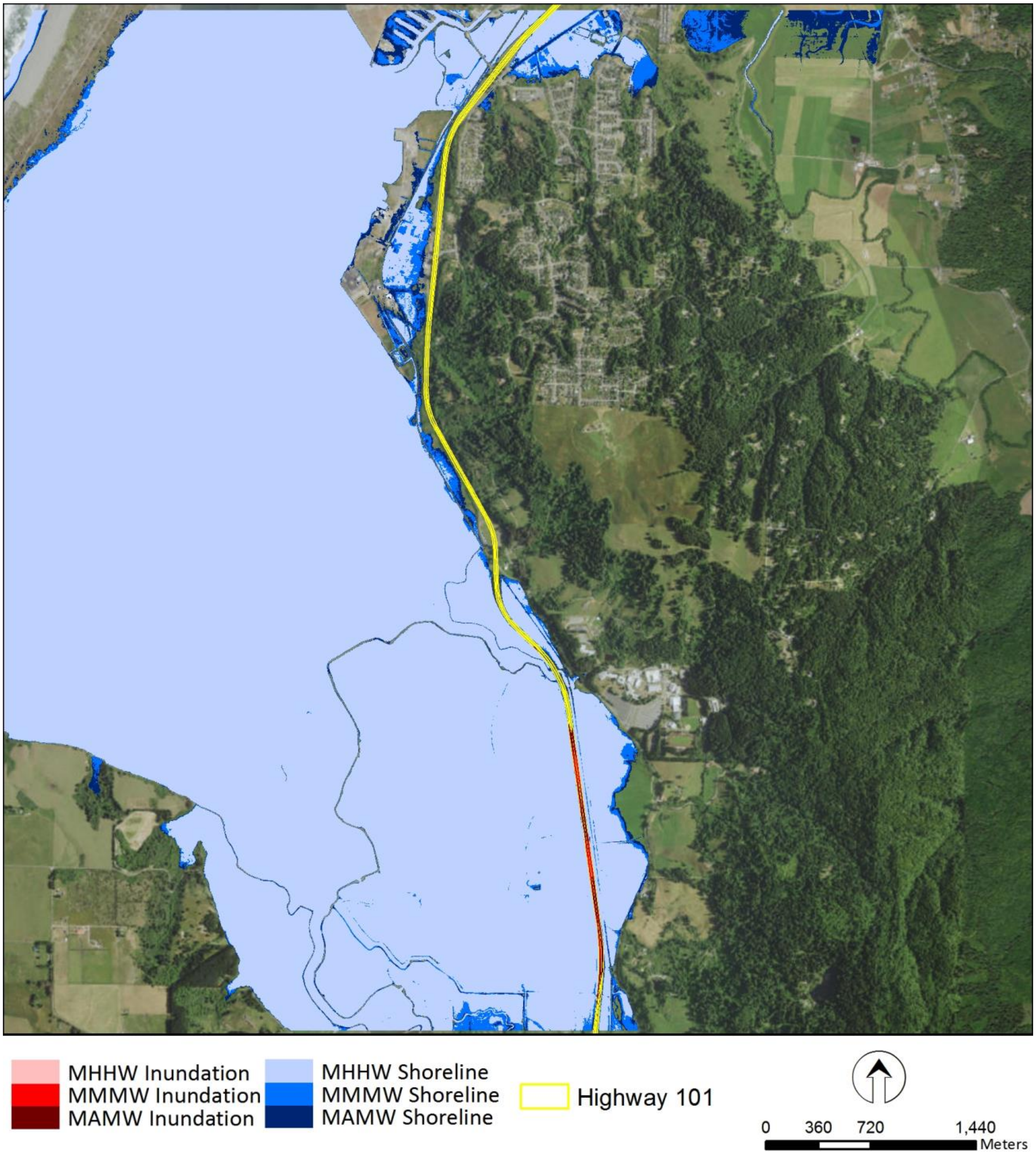


Figure 41: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 High Sea Level Rise Projection:

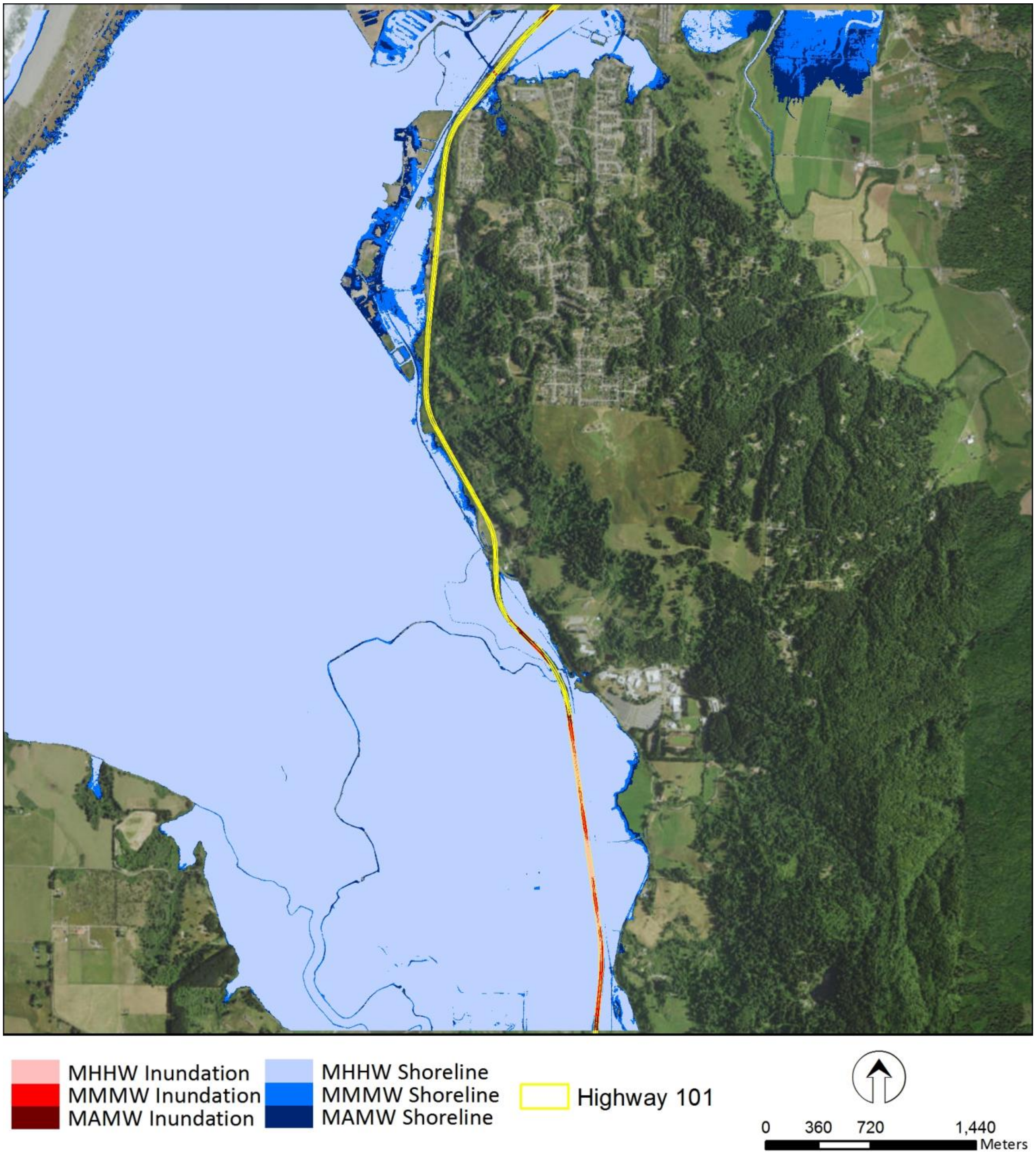


Figure 42: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection:

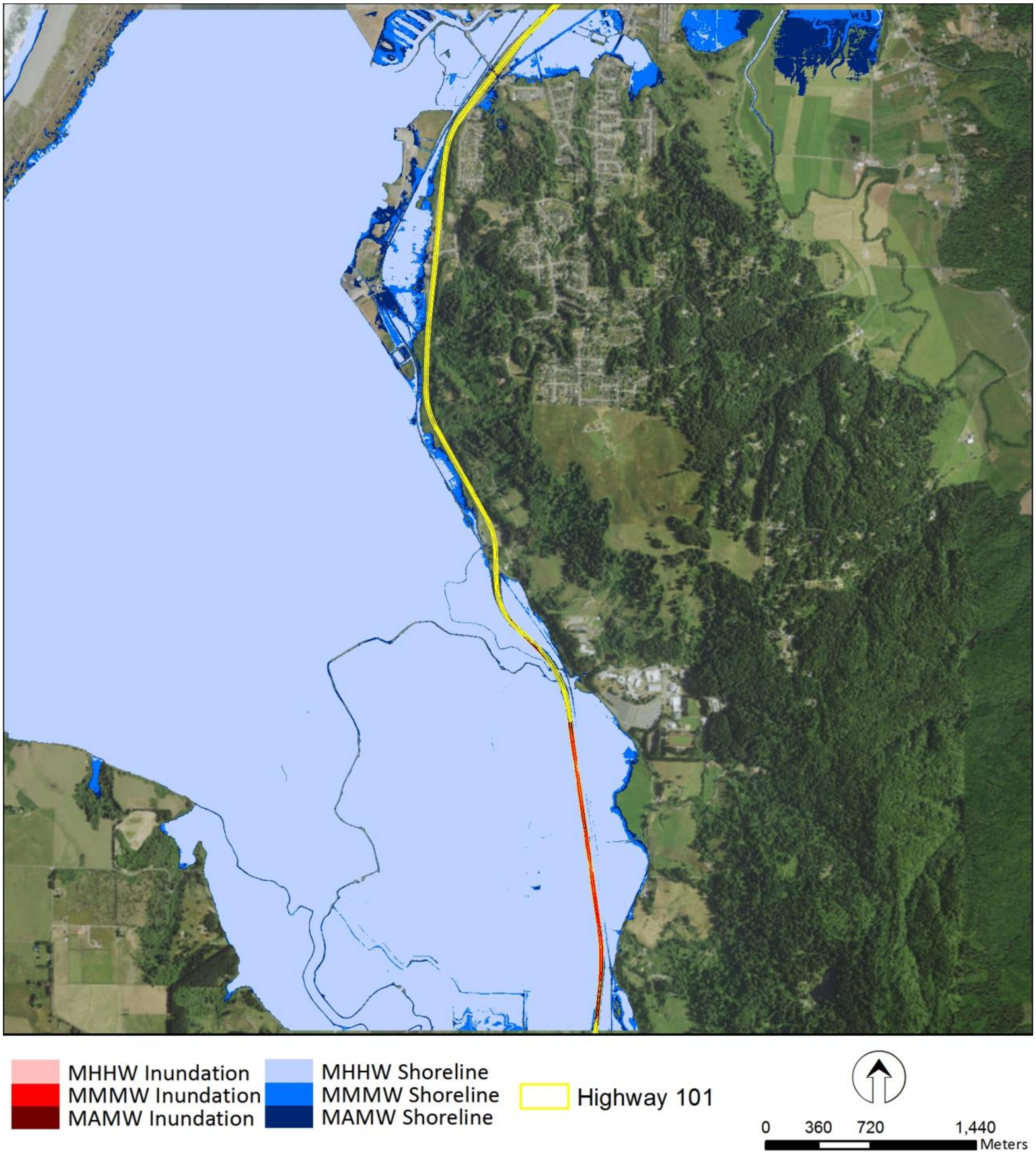


Figure 43: Map showing inundation for: (MHHW/ MMMW/ MAMW).

<u>2050 Low Sea Level Rise Projection:</u>

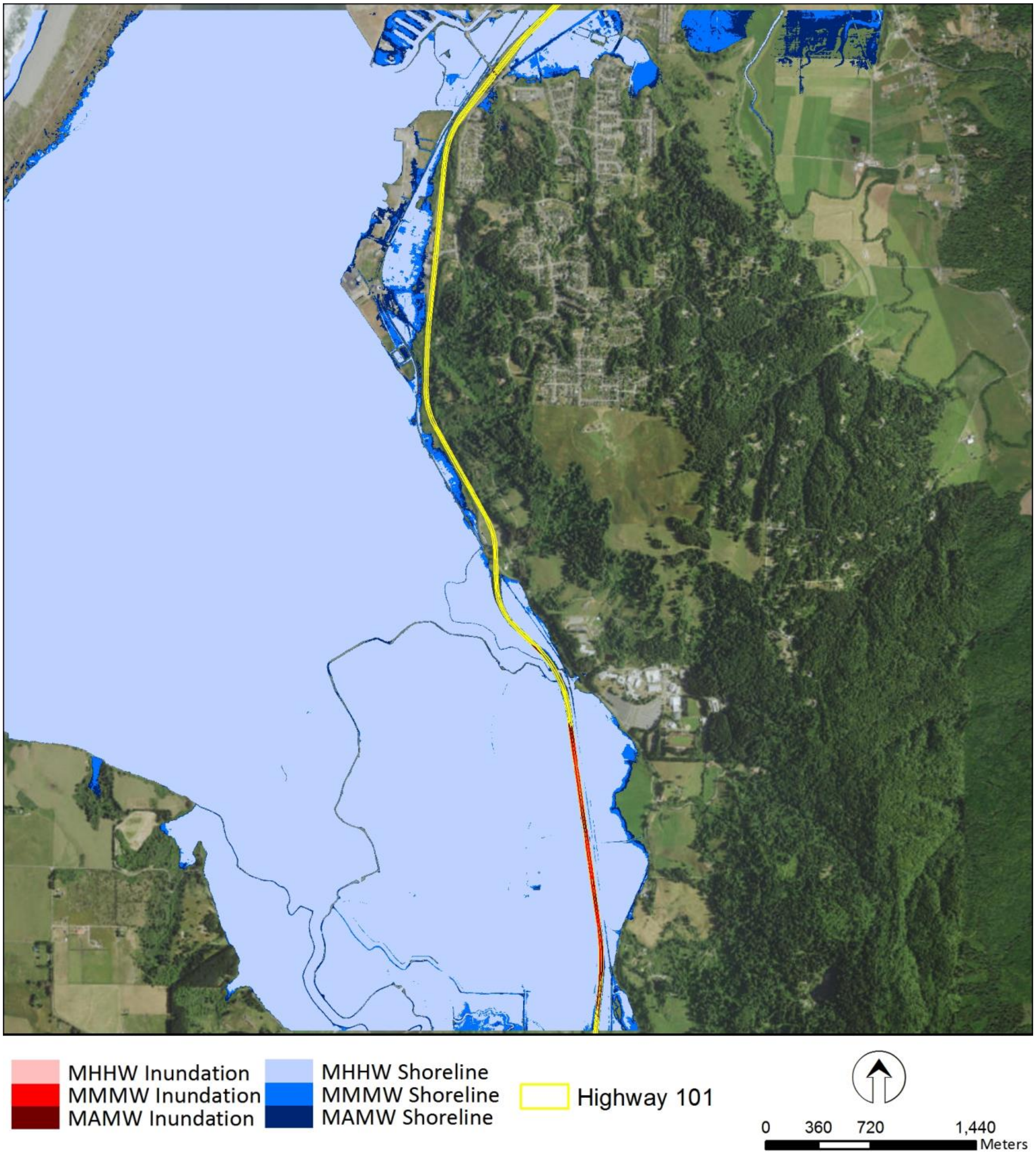


Figure 44: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2030 Mid Sea Level Rise Projection - POI:

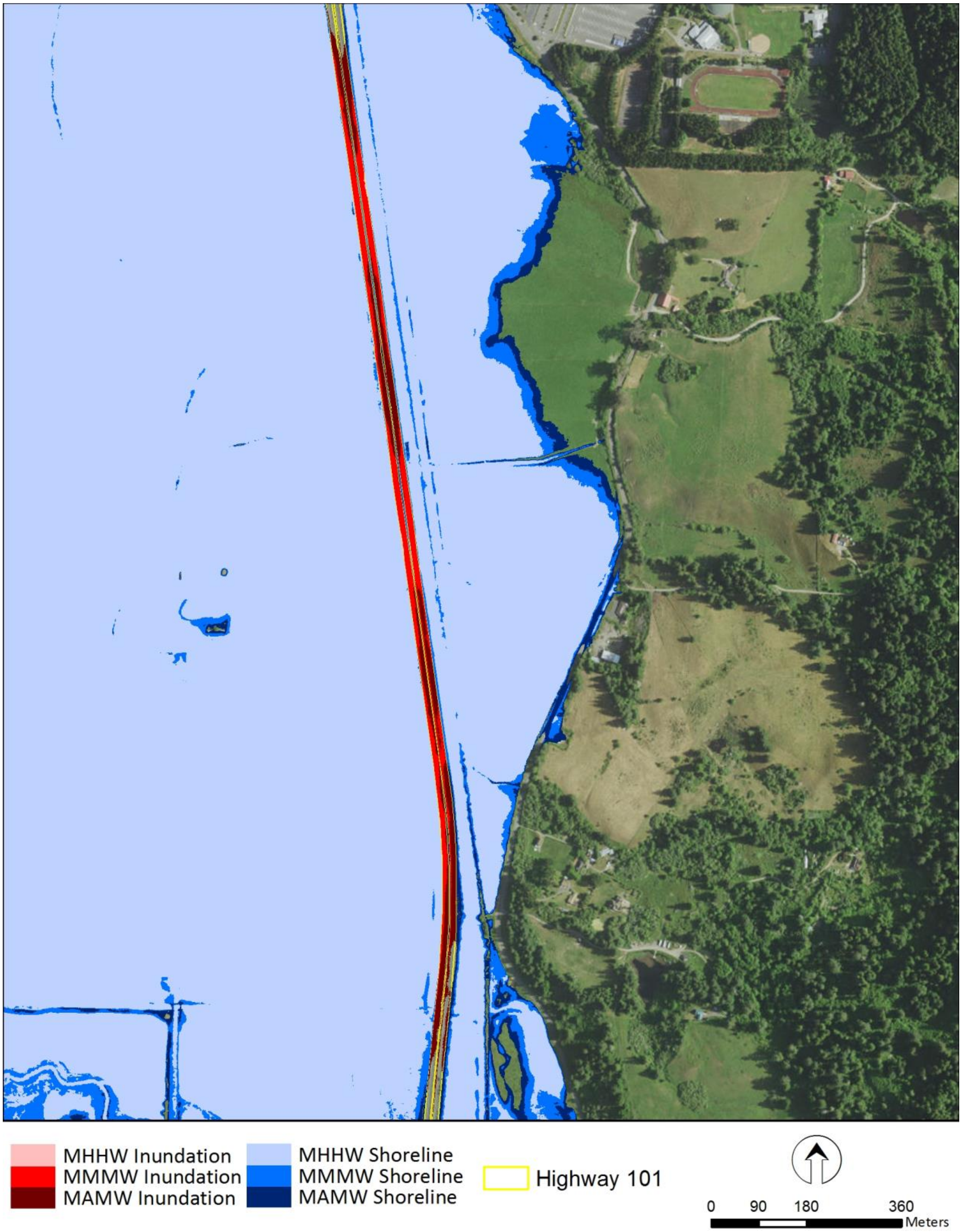


Figure 45: Map showing inundation for: (MHHW/ MMMW/ MAMW).

2050 Mid Sea Level Rise Projection - POI:

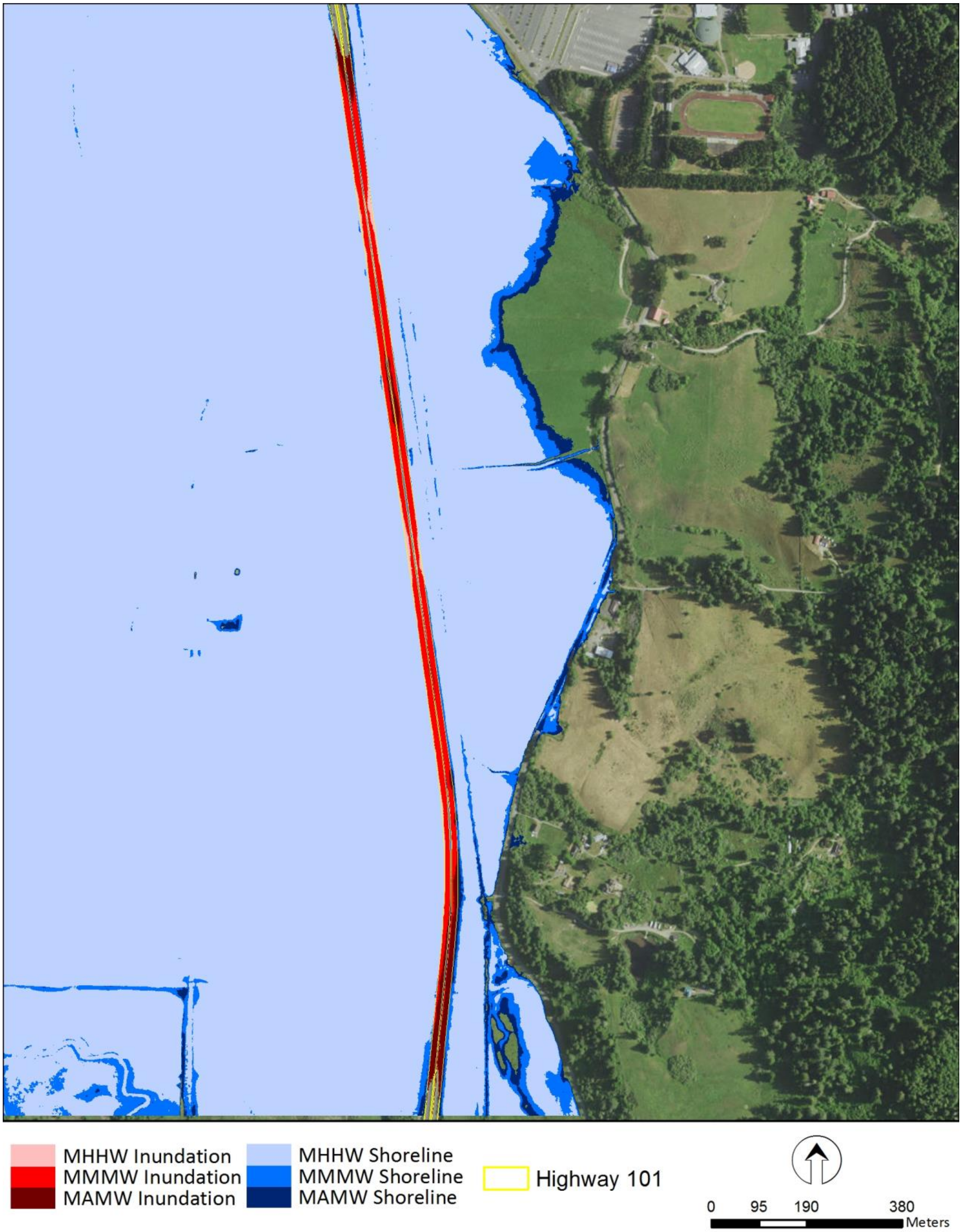


Figure 46: Map showing inundation for: (MHHW/ MMMW/ MAMW).

Appendix 2 Tables and Graphs

Table 4: Table showing tide heights for different sea level rise projection thresholds - high, medium, and low. All values are in feet and are based on the NAVD88 vertical datum. These values were determined using predicted tidal patterns. Tidal height tables for the areas of study are located in Appendix 2. RSLRHP- Relative Sea Level Rise to the Humboldt Plate, MLLW- Mean Lower Low Water, MSL-Mean Sea Level, MHW-Mean High Water

YEAR	**RSLRHP**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**	**MMMW**	**MAMW**
2015	0	-0.3	0.9	3.4	5.8	**6.5**	**7.7**	**8.8**
2030	0.9	0.6	1.8	4.3	6.7	**7.4**	**8.6**	**9.7**
2050	1.9	1.6	2.8	5.3	7.7	**8.4**	**9.6**	**10.7**
YEAR	**RSLRMP**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**	**MMMW**	**MAMW**
2015	0	-0.3	0.9	3.4	5.8	**6.5**	**7.7**	**8.8**
2030	0.6	0.3	1.5	4	6.4	**7.1**	**8.3**	**9.4**
2050	1.1	0.8	2	4.5	6.9	**7.6**	**8.8**	**9.9**
YEAR	**RSLRLP**	**MLLW**	**MLW**	**MSL**	**MHW**	**MHHW**	**MMMW**	**MAMW**
2015	0	-0.3	0.9	3.4	5.8	**6.5**	**7.7**	**8.8**
2030	0.4	0.1	1.3	3.8	6.2	**6.9**	**8.1**	**9.2**
2050	0.7	0.4	1.6	4.1	6.5	**7.2**	**8.4**	**9.5**

Meters² and percentage of Highway 101 Inundation - for 2030

Highway 101 Section	Low Projection Sea Level Rise			Mid Projection Sea Level Rise			High Projection Sea Level Rise			
	MHHW	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**Total Area**
Eureka Slough to Brainard	0.15	1,067.20	17,279.09	0.74	2,052.70	21,583.17	2.319617	4,061.45	24,404.46	27,049.65
	0.001%	3.945%	63.879%	0.003%	7.589%	79.791%	0.009%	15.015%	90.221%	
King Salmon to Hookton Slough	364.78	17,173.85	41,477.78	652.93	21,965.70	43,131.02	2,181.96	32,988.06	47,302.12	169,913
	0.215%	10.107%	24.411%	0.384%	12.928%	25.384%	1.284%	19.415%	27.839%	
Brainard to Arcata	1,705.43	3,243.27	25,354.31	1,755.79	4,431.30	29,740.78	1,931.16	9,802.59	39,322.29	168,699.78
	1.011%	1.923%	15.029%	1.041%	2.627%	17.629%	1.145%	5.811%	23.309%	
Eureka Slough	3,935.87	4,497.53	11,288.62	3,947.94	4,795.69	13,780.59	3,965.42	5,452.53	20,511.46	95,650.14
	4.115%	4.702%	11.802%	4.127%	5.014%	14.407%	4.146%	5.700%	21.444%	

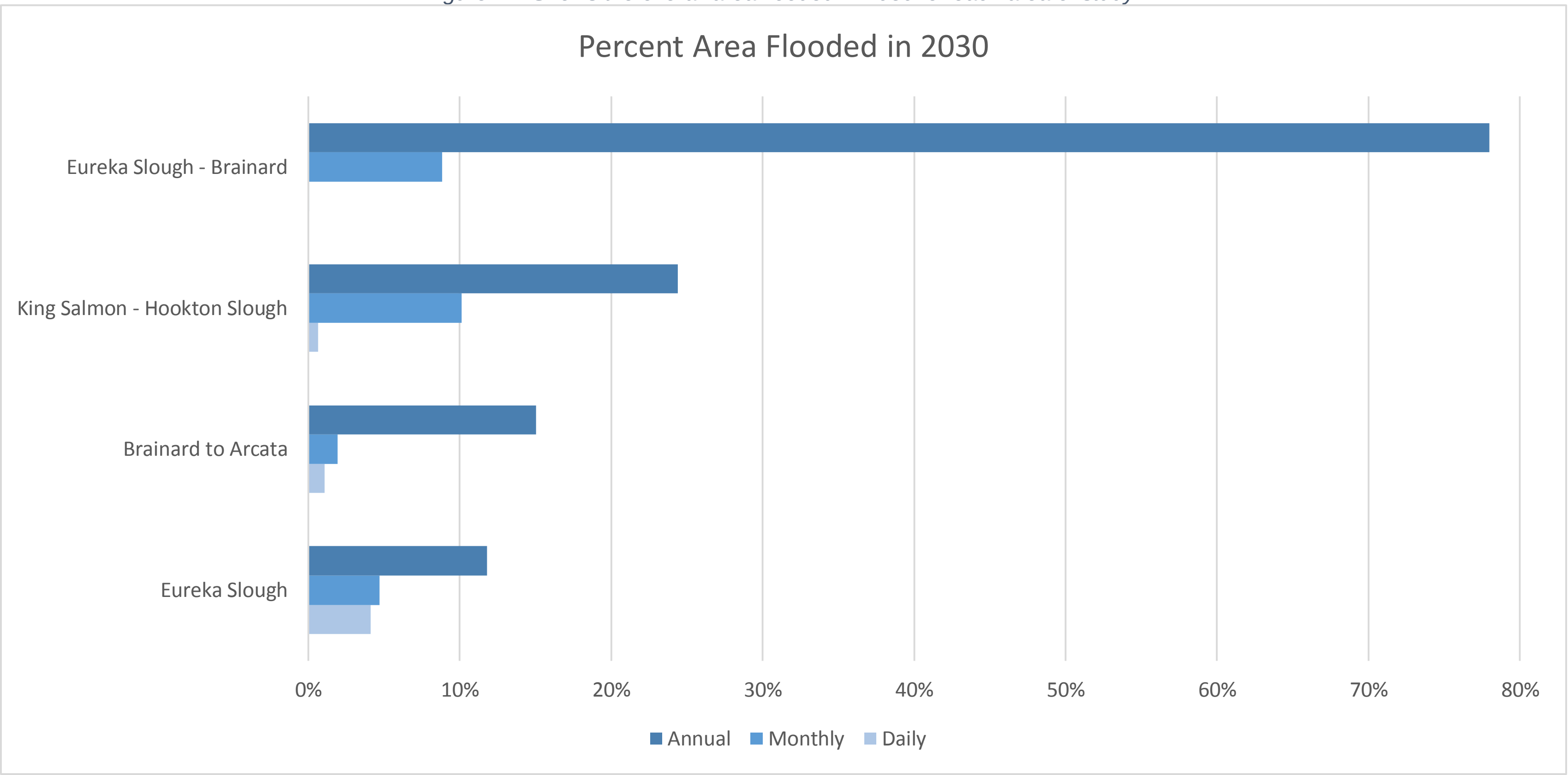
Table 5: Highway 101 was divided into 4 parts. The area is in m2 of the highway that will be inundated by MHHW, MMMW, and MAMW for low, mid, and high projections of sea level rise for 2030.

Meters² and percentage of Highway 101 Inundation - for 2050

Highway 101 Section	Low Projection Sea Level Rise			Mid Projection Sea Level Rise			High Projection Sea Level Rise			
	MHHW	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**MHHW**	**MMMW**	**MAMW**	**Total Area**
Eureka Slough to Brainard	12.64	3,254.28	23,913.04	132.69	10,599.48	26,799.69	4527.89	25,987.96	27,049.65	27,049.65
	0.047%	12.031%	88.404%	0.491%	39.185%	99.076%	16.739%	96.075%	100.000%	
King Salmon to Hookton Slough	1179.69	27,567.98	45,126.32	3965.97	36,975.49	49,532.75	24,585.67	47,404.61	58,906.37	169,913
	0.694%	16.225%	26.558%	2.334%	21.761%	29.152%	14.470%	27.899%	34.669%	
Brainard to Arcata	1,835.49	6,858.87	34,238.12	2,102.72	14,916.29	44,661.45	7,138.38	39,345.95	61,348.72	168,699.78
	1.088%	4.066%	20.295%	1.246%	8.842%	26.474%	4.231%	23.323%	36.366%	
Eureka Slough	3,962.42	5,324.92	16,281.80	4,001.92	7,877.09	22,667.83	4,869.83	20,270.07	33,306.04	95,650.14
	4.143%	5.567%	17.022%	4.184%	8.235%	23.699%	5.091%	21.192%	34.821%	

Table 6: Highway 101 was divided into 4 parts. The area in m2 of the highway that that will be inundated by MHHW, MMMW, and MAMW for low, mid, and high projections of sea level rise for 2050.

Figure 47: Shows the overall area flooded in 2030 for each area of study.



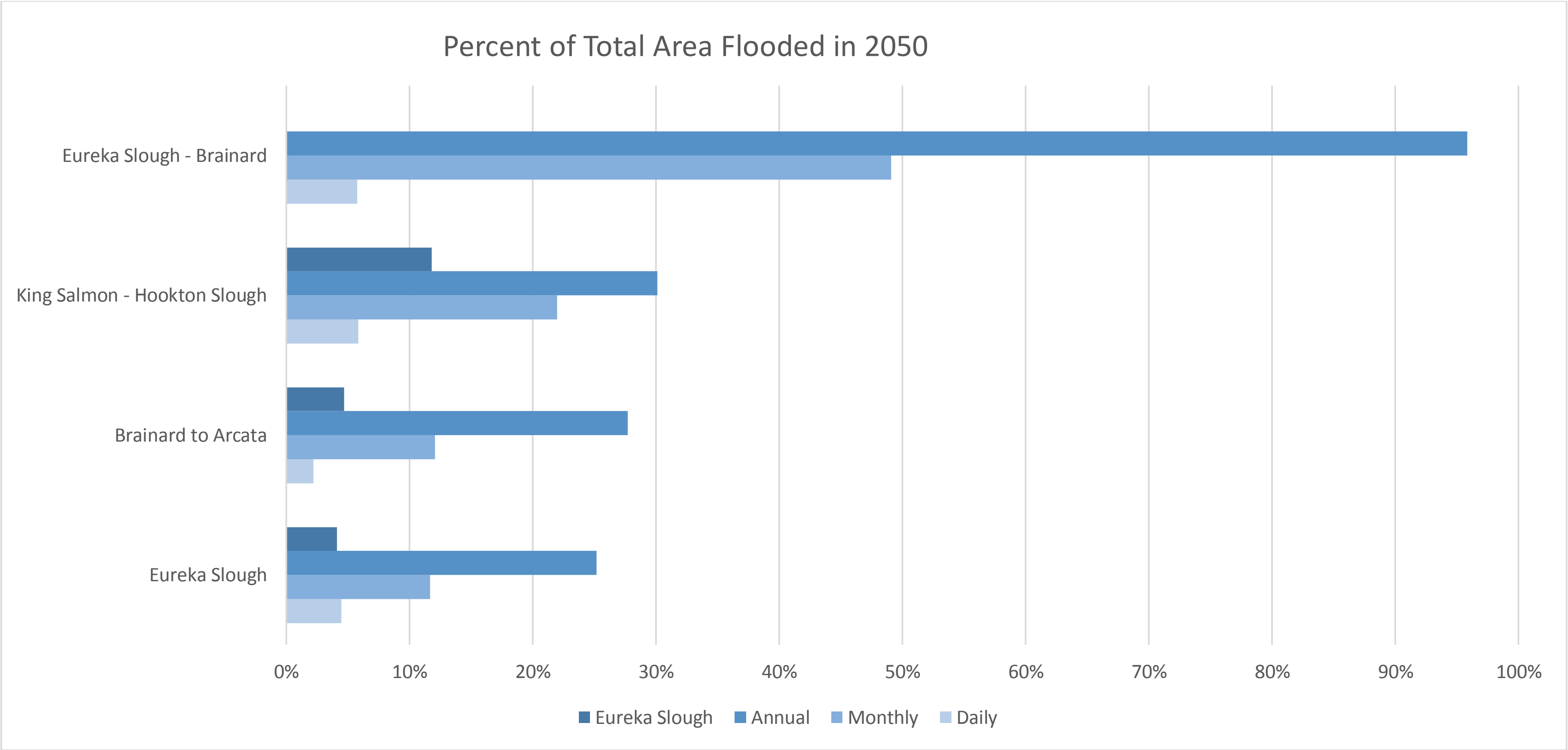


Figure 48: Shows the overall area flooded in 2050 for each area of study.

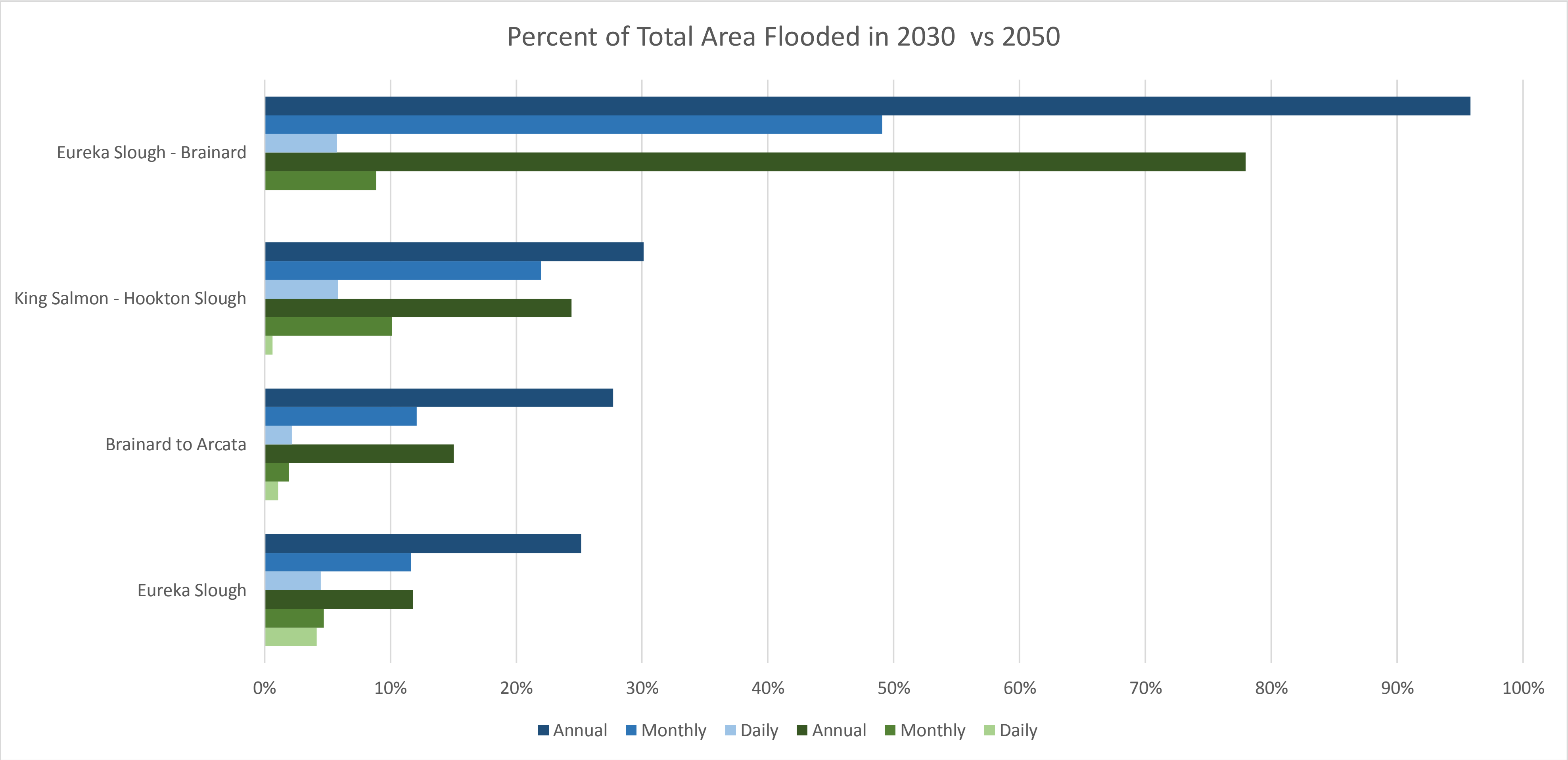


Figure 49: Shows the overall area flooded in 2030 and 2050 for each area of study. 2030- Blue, 2050- Green

Table 7: Sea Level Rise values for the Eureka Slough to Brainard highway section.

YEAR	RSLRHP	MHHW	MMMW	MAMW	
2012	0.0548	2.1450	2.5495	2.8635	Low
2030	0.1320	2.2770	2.6815	2.9955	
2050	0.2269	2.3719	2.7764	3.0904	
YEAR	RSLRMP	MHHW	MMMW	MAMW	
2012	0.0623	2.1450	2.5495	2.8635	Medium
2030	0.1760	2.3352	2.7397	3.0537	
2050	0.3405	2.5483	2.9528	3.2668	
YEAR	RSLRLP	MHHW	MMMW	MAMW	
2012	0.0811	2.1450	2.5495	2.8635	High
2030	0.2809	2.3877	2.7922	3.1062	
2050	0.5936	2.6749	3.0794	3.3934	

Table 8: Sea Level Rise values for King Salmon to Hookton Slough highway section.

YEAR	RSLRHP	MHHW	MMMW	MAMW	
2012	0.0548	2.0573	2.4503	2.7598	Low
2030	0.1320	2.1893	2.5823	2.8918	
2050	0.2269	2.2842	2.6772	2.9867	
YEAR	RSLRMP	MHHW	MMMW	MAMW	
2012	0.0623	2.0573	2.4503	2.7598	Medium
2030	0.1760	2.2333	2.6263	2.9358	
2050	0.3405	2.3978	2.7908	3.1003	
YEAR	RSLRLP	MHHW	MMMW	MAMW	
2012	0.0811	2.0573	2.4503	2.7598	High
2030	0.2809	2.3382	2.7312	3.0407	
2050	0.5936	2.6509	3.0439	3.3534	

Table 9: Sea Level Rise values for Brainard to Arcata highway section.

YEAR	RSLRHP	MHHW	MMMW	MAMW	
2012	0.0548	2.2122	2.5652	2.8767	Low
2030	0.1320	2.3442	2.6972	3.0087	
2050	0.2269	2.4391	2.7921	3.1036	
YEAR	RSLRMP	MHHW	MMMW	MAMW	
2012	0.0623	2.2122	2.5652	2.8767	Medium
2030	0.1760	2.3882	2.7412	3.0527	
2050	0.3405	2.5527	2.9057	3.2172	
YEAR	RSLRLP	MHHW	MMMW	MAMW	
2012	0.0811	2.2122	2.5652	2.8767	High
2030	0.2809	2.4931	2.8461	3.1576	
2050	0.5936	2.8058	3.1588	3.4703	

Table 10: Sea Level Rise values for the Eureka Slough highway section.

YEAR	RSLRHP	MHHW	MMMW	MAMW	
2012	0.0548	2.1543	2.5593	2.8697	Low
2030	0.1320	2.2863	2.6913	3.0017	
2050	0.2269	2.3812	2.7862	3.0966	
YEAR	RSLRMP	MHHW	MMMW	MAMW	
2012	0.0623	2.1543	2.5593	2.8697	Medium
2030	0.1760	2.3303	2.7353	3.0457	
2050	0.3405	2.4948	2.8998	3.2102	
YEAR	RSLRLP	MHHW	MMMW	MAMW	
2012	0.0811	2.1543	2.5593	2.8697	High
2030	0.2809	2.4352	2.8402	3.1506	
2050	0.5936	2.7479	3.1529	3.4633	