Modeling the Impacts of Sea Level Rise on Estuarine Habitats in the Point No Point Treaty Area

Final Project Technical Report

Prepared by
Tim Cullinan

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Point No Point Treaty Council
19472 Powder Hill Place NE, Suite 210
Poulsbo, Washington 98370

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TITLE

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INTRODUCTION

It is certain that as global temperatures rise in the twenty-first century, seal levels will also rise. This will inevitably have impacts on coastal ecosystems caused by increased inundation of existing tidal flats, beaches, and both salt and coastal freshwater marshes. This has the potential to detrimentally impact important Tribal resources.

The scale of threats to Tribal resources will depend on the amount of ecological change caused by sea level rise. To allow resource managers to assess the potential impacts on fish, shellfish, and wildlife, we conducted a pilot study to map the locations and extent of existing estuarine habitats and to model the potential changes in quantity and geographic extent of these habitats. This report describes our efforts to conduct such an assessment on three prominent estuaries in the Point No Point treaty area. It includes an evaluation of the Sea Level Affecting Marshes Model (SLAMM) as a tool for predicting future changes in estuarine habitats as seal levels continue to rise in the remainder of the 21st century.

METHODS

The modeling exercise was conducted in three estuaries in eastern Jefferson County, Washington—the Duckabush, Quilcene, and Snow/Salmon Creek (hereinafter referred to as Snow Creek). The Duckabush and Quilcene are estuaries on Hood Canal and the Snow Creek is at the southern end of Discovery Bay on the Strait of Juan de Fuca (Figure 1). The three estuaries collectively comprise approximately 6 km^2 of coastal wetlands, beaches, and tidal flats (Table 1). The Duckabush and Snow estuaries have been modified by construction of high berms to accommodate U.S. 101, a two-lane federal highway. The berms partially alter tidal flow but high bridges allow tidal action to extend landward of the highway. Development in the uplands surrounding the estuaries is light, consisting primarily of agriculture, rural residential, and small business commercial land uses. Dikes were built in the Quilcene in the past to protect agricultural fields, but those dikes are no longer functional. No dikes occur in the other two estuaries, but there is an abandoned railroad grade running parallel to the federal highway in the Snow Creek estuary.

Existing estuarine habitats were mapped as part of Estuary Baseline Study (PNPTC Technical Report 2). That study mapped and quantified existing areas of intertidal and adjacent habitats to include beaches, tidal flats, tidal salt marshes, transitional marshes, freshwater wetlands, adjacent open water and adjacent dry uplands. The maps were developed using 2015-2016 aerial photographs and field verification. The final product of that study was an ArcGIS geo-database containing year 2015 land cover in and around the three featured estuaries.

We modeled changes in shoreline and estuarine habitat changes using the Sea Level Affecting Marshes Model (SLAMM) version 6.7 (Clough 2014). The SLAMM predicts the effects of inundation, erosion, and accretion under various sea level rise scenarios over a range of time frames. This allowed the identification of the locations and the extent of potential retreat zones where intertidal habitats are free to migrate landward as sea level rises, and the locations and extent of areas where barriers to inland migration occur. This, in combination with our land cover database, yielded estimates of changes in the location and extent of key estuarine habitats and estimates of potential habitat gains and losses resulting from future rising water levels. For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.2 Technical Documentation (Clough et al. 2016). This document is available at http://warrenpinnacle.com/prof/SLAMM.

Figure 1. Vicinity map.

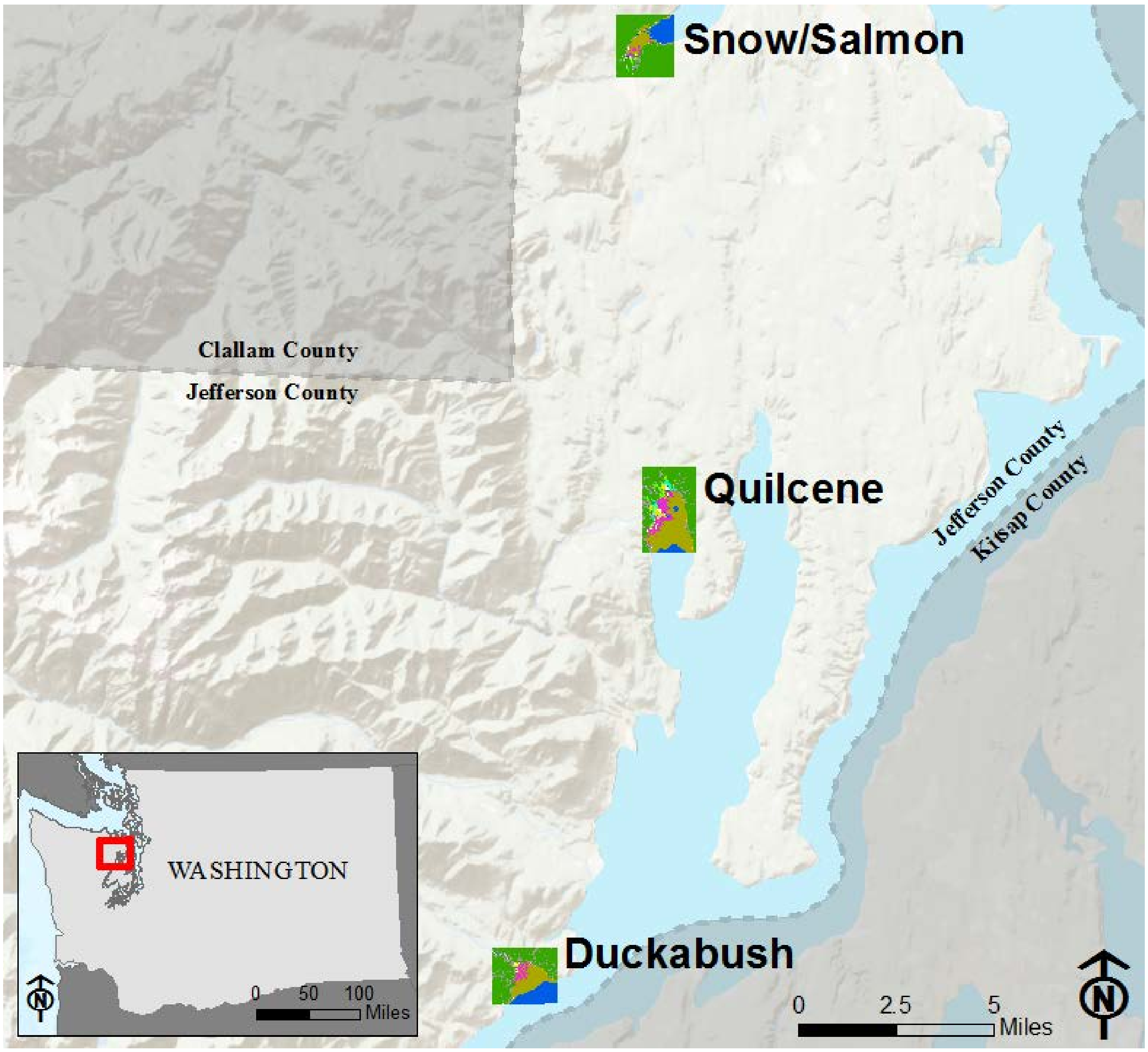


Table 1. Extent of coastal wetlands in the three estuaries analyzed in this project in 2016. All area measurements are in hectares.

Coastal Habitat Type	Duckabush	Quilcene	Snow Creek
Developed Dry Land	51.81	55.65	20.38
Undeveloped Dry Land	302.10	329.05	433.66
Swamp	1.18	19.33	1.63
Inland Fresh Marsh	0.00	15.69	2.30
Tidal Fresh Marsh	0.00	15.76	0.55
Transitional Salt Marsh	0.80	0.69	4.33
Regularly Flooded Marsh	25.55	59.54	12.87
Estuarine Beach	1.64	2.91	0.68
Tidal Flat	113.95	234.51	56.34
Inland Open Water	1.65	2.98	1.12
Riverine Tidal	0.00	4.23	0.41
Estuarine Open Water	120.37	31.46	86.51
Irregularly Flooded Marsh	2.65	8.99	0.71
Inland Shore	2.14	0.13	0.00
Tidal Swamp	0.77	0.88	2.02

Using the year 2016 as a starting point (the date of the aerial photographs used to assess existing conditions), we used the SLAMM to simulate changes is estuarine habitat in 25-year increments between 2025 and the year 2100. Our original intent was to model sea level rise using the low, medium, and high severity scenarios. Several Puget Sound modeling efforts used the so-called A1B scenario, which predicted sea level increases ranging from 0.21 to 0.69 meters by the year 2100 2100 (Clough 2007, Clough and Larson 2010, Jamestown S'Klallam Tribe 2013). Those scenarios ultimately were not used in our analysis because they became outdated as new data revealed that they substantially underestimated potential sea level rise. In late 2018 the U.S. Global Change Research Program released its Fourth National Climate Assessment (Sweet et al. 2017). That report provided more timely and estimates and higher levels of confidence of predicted sea level rise. In our models, we used the National Climate Assessment's estimate of sea level rise of 1.3 meters by the year 2021.

The SLAMM works by simulating the dominant processes involved in wetland conversions–primarily inundation (both spatial and temporal), erosion, and accretion. The model requires the input of a number of user defined parameters that describe the local physical environment. This model used geographic data and was processed using the Environmental Systems Research Institute (ESRI) ArcMap® 10 Geographic Information System (GIS) software. Additionally, ArcMap® was used to combine and display the model outputs in map format. See: http://www.esri.com/.
Detailed information on SLAMM is available online at: http://www.warrenpinnacle.com/prof/SLAMM/.

The three fundamental inputs for the SLAMM are 1) a wetlands inventory data layer, 2) an elevation data layer, and 3) a slope data layer. Additional inputs include the historic sea level rise trend, a correction factor to calibrate tide level to the elevation data, the daily tidal range, the height of salt water above mean tide level, and erosion and accretion rates in different marsh types. The inputs to the SLAMM simulations for all three estuaries are summarized in Table 3. The inputs used in our modeling effort were as follows:

Elevation and Slope Data
The digital elevation data used in our simulations was 2005 LiDAR made available through the Puget Sound LiDAR Consortium. These are raster maps with pixel resolution size of 6 feet (1.828 m) and vertical elevations expressed in feet. All digital elevation layers were projected in ArcGIS to convert feet to meters in both horizontal and vertical dimensions. Slope rasters were derived from the LiDAR data using the Spatial Analyst slope tool in ArcGIS.

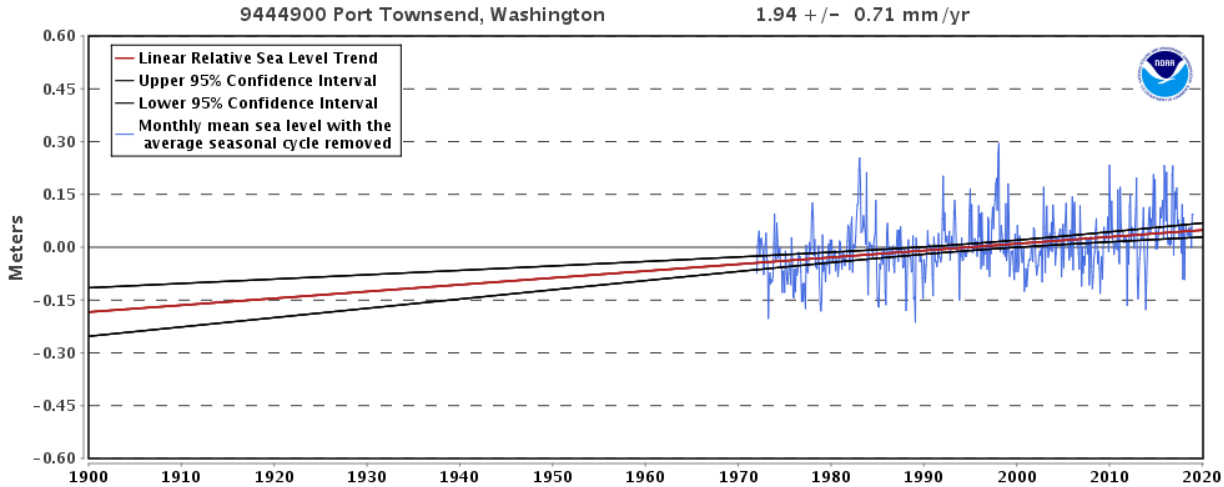
Wetlands Data Layer
The developers of the SLAMM recommend using National Wetlands Inventory (NWI) data as the input for the wetlands layer. Unfortunately it was found that the most recent NWI data available were nearly 30 years old. Field verification revealed that these data layers were no longer accurate. After consulting with the SLAMM developers, a decision was made to use a hybrid of the Point No Point Treaty Council's 2016 land cover database and the NWI data. For each of the estuaries we ran the SLAMM using 1980 NWI data to simulate levels of inundation in 2016. Then we overlaid that output with our more accurate land cover classes from 2016, and examined the land cover shapefiles to estimate the wetland type that would result based on the level of inundation, and edited the land cover database accordingly. We developed a procedure to crosswalk the newly created hybrid land cover classes--that more accurately depicted the current land cover classes--to the set of wetland classes compatible with the SLAMM (Clough et al. 2016). This required adding a step in preparing the wetlands layer to run in a SLAMM simulation, but the result was a greater level of confidence in the accuracy of our wetlands data input.

Historic Sea Level Rise
This parameter is used to estimate subsidence or uplift by comparison with the global rate. For all three estuaries modeled, we used the value 1.94 mm/year. This value was obtained from the Port Townsend, Washington NOAA station (https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?id=9444900), the only station in the vicinity of the three estuaries to make this metric available. The rate of sea level rise for this refuge is slightly higher than the estimated global historic sea level rise (approximately 1.7 mm/year). (Figure 2.)

MTL minus NAVD88 Vertical Datum Correction
This parameter is used to convert from a geodetic vertical datum, in this case NAVD88, to a datum that is relative to mean tide level (MTL). For the Duckabush and Quilcene simulations, MTL and NAVD88 values were obtained from the NOAA station at Whitney Point, Washington, a site midway between the Duckabush delta and Quilcene Bay. The MTL-NAVD88 value at this location is 1.258 meters. For the Snow Creek simulation, we obtained MTL and NAVD88 values from the NOAA station at Naval Air Station Whidbey Island, the nearest NOAA station that

provides that information. The MTL-NAVD88 value at this location is 1.272 meters.

Figure 2. Relative Sea Level Trend, Port Townsend, Washington



Great Diurnal Tidal Range
This parameter measures the vertical difference between mean lower low water (MLLW) and mean higher high water (MHHW) to capture the tidal range of a site. The sources of values of this input were the NOAA stations at Point Whitney (3.525 m) for the Duckabush and Quilcene simulations and at Port Townsend (2.597) for Snow Creek.

Salt Elevation
Salt elevation is described as the elevation at which dry land and freshwater wetlands begin, often defined as the elevation that is inundated by salt water less than every thirty days. The value used for all three simulations was 1.5 m above mean tide level.

Accretion Rate (all marsh types)
This parameter describes the vertical growth in elevation of marshes due to the accumulation of organic and mineral sediment. For all three estuary simulations we set accretion rates at 3.6 mm/year for regularly flooded marsh (salt marsh), 3.75 mm/year for irregularly flooded marsh, and to 4.0 mm/year for tidal fresh marsh. These values were based on regional measurements (Thom 1992).

Erosion
This parameter describes the annual rate of horizontal erosion due to wave action. For all three estuary simulations we set erosion rates for tidal flats and estuary beaches to 0.2 m/year (Keuler 1988). In this model marsh erosion was set to equal 2.0 m per year and swamp erosion was set to 1.0 m/year (measured on the horizontal dimension). These values are SLAMM defaults, and were used because specific local erosion rate data were not available. After the study was completed it revealed that these values probably overestimated marsh and swamp erosion (see discussion section below).

Beach Sedimentation Rate
For all three simulations this input was set at 0.5 mm/year. This is the SLAMM default value.

Table 3. Input parameter values in the SLAMM simulations.

	Estuary		
Parameter	Duckabush	Quilcene	Snow Creek
Wetland Data Photo Date	2016	2016	2016
Elevation Data Date	2005	2005	2005
Direction Offshore	east	south	north
Historic SLR Trend (mm/yr)	1.94	1.94	1.94
MTL-NAVD88 (m)	1.258	1.258	1.272
GT Great Diurnal Tide Range (m)	3.587	3.4686	2.597
Salt Elevation (m above MTL)	1.5	1.5	1.5
Marsh Erosion (horz. m /yr)	2.0	2.0	2.0
Swamp Erosion (horz. m /yr)	1.0	1.0	1.0
Tidal Flat Erosion (horz. m /yr)	0.2	0.2	0.2
Regularly Flooded Marsh Accretion (mm/yr)	3.6	3.6	3.6
Irreg. Flood Marsh Accretion (mm/yr)	3.75	3.75	3.75
Tidal Fresh Marsh Accretion (mm/yr)	4.0	4.0	4.0
Beach Sedimentation Rate (mm/yr)	0.5	0.5	0.5

Because existing development can influence inundation patterns as sea level rises, the SLAMM models were run in two different modes to obtain statistics of the impact that existing development will have on the ability of coastal wetlands to migrate landward. In “protected” mode, the assumption is made that protective actions (such as building dikes or berms) will be taken to prevent wetlands from migrating onto developed lands. In the “not protected” mode the SLAMM allows wetlands to migrate onto developed areas despite the highly altered upland condition. The utility of running the model in these two different modes allows a comparison as to how development will influence the overall migration of wetlands and to show the potential for conservation and restoration efforts. Developed areas were defined and mapped using the PNPTC land cover database.

RESULTS

<u>Summary of changes 2016 to 2100</u>

<u>Duckabush</u>:

In the scenario in which developed dry land is not protected, major changes will be seen in the loss of dry land, regularly flooded marsh, and tidal flats. The only two categories that increase will be transitional salt marsh and estuarine open water. Transitional salt marsh will increase by 3.39 hectares, a four-fold increase. Nearly 19 hectares will be added to the open water category, with losses of nearly 14 hectares of swamp, marshes, and tidal flats.

If developed dry land is protected, major changes will be seen in the loss of undeveloped dry land, regularly flooded marsh, and tidal flats. As in the case of not protecting developed land, the only gains will be in transitional salt marsh and estuarine open water. Transitional salt marsh will increase by 1.40 hectares, a nearly two-fold increase. Nearly 19 hectares will be added to the open water category. There will be losses of approximately 15 hectares of swamp, marshes, and tidal flats. The greatest loss will be in regularly flooded marsh, which will decline by nearly 8 hectares, a 31% loss.

The difference between the protection vs the no-protection mode is that in the protection mode, there will be a 1.9 hectare greater loss of regularly flooded salt marsh. There will be only half as much gain of new transitional salt marsh if developed land is protected. Swamps, tidal flats and estuarine open water will be affected equally under both modes.

Estimates of the predicted extent of each of the SLAMM categories under both protection scenarios in the years 2016, 2015, 2050, 2075, and 2100 in the Duckabush estuary are provided in Table A-1 in Appendix A. Maps of the locations of existing (2016) and year 2100 wetland types are provided in Figures A1, A2, and A3 in Appendix A.

<u>Quilcene:</u>

In the event that dry land is not protected, major changes will occur in the losses of dry land, swamp, inland fresh marsh, riverine tidal habitat, and irregularly flooded marsh. As in the case of the Duckabush, transitional salt marsh and estuarine open water will increase substantially. Unlike the Duckabush however, in the Quilcene tidal flats will increase substantially rather than decrease, and the effects on regularly flooded marshes will be negligible. Nearly 35 hectares will be added to open water and tidal flats, and nearly 20 hectares to transitional salt marsh. Approximately 29.5 hectares will be lost from freshwater wetlands and irregularly flooded salt marsh.

If developed dry land is protected, major changes will be seen in the loss of swamp, inland fresh marsh, regularly flooded marsh, riverine tidal habitat, and irregularly flooded marsh. Transitional salt marsh, tidal flats, and estuarine open water will increase substantially. Nearly 35 hectares will be added to open water and tidal flats, and transitional salt marsh will increase by about 16 hectares. More than 23 hectares of freshwater wetlands will be lost. Irregularly flooded salt marsh will decline by 6 hectares and 2 hectares will be lost from regularly flooded salt marsh.

Whether or not developed dry land is protected will have little impact on most habitat categories. The only major differences between the protection and no protection modes is that in the protection mode, regularly flooded marsh will be affected, with a loss of 2 hectares, and there will be about 3.5 fewer hectares of new transitional salt marsh created. Swamps, inland fresh marshes, irregularly flooded marshes, tidal flats and estuarine open water will be affected equally under both modes.

Estimates of the predicted extent of each of the SLAMM categories under both protection scenarios in the years 2016, 2015, 2050, 2075, and 2100 in the Quilcene estuary are provided in Table A-2 in Appendix A. Maps of the locations of existing (2016) and year 2100 wetland types are provided in Figures A4, A5, and A6 in Appendix A.

Snow Creek:

Under the scenario in which developed dry land is not protected from encroaching sea water, major changes will be substantial losses only of dry land and tidal flats. There will be significant increases in regularly flooded salt marsh and estuarine open water. Moderate losses will occur in freshwater wetlands, riverine habitats, and tidal swamps, and moderate gains will occur in transitional salt marsh. There will be no detectable change in irregularly flooded salt marsh. Approximately 9.5 hectares will be lost from tidal flats, but 5 hectares of new regularly flooded marsh will be created, as will 1.6 hectares of transitional salt marsh. Estuarine open water will increase more than 21 hectares. All freshwater and riverine habitats combined will decline by less than 2 hectares, and there will be a loss of 0.72 hectares of tidal swamp.

If developed dry land is protected, the major changes will be the loss of undeveloped dry land and tidal flats. Regularly flooded marsh and transitional salt marsh will increase moderately and the estuarine open water will see a substantial increase. As in the no-protection scenario, moderate losses will occur in freshwater wetlands, riverine habitats, and tidal swamps. There will be no detectable change in irregularly flooded salt marsh. Approximately 9.6 hectares will be lost from tidal flats, but only 2.7 hectares of new regularly flooded marsh will be created to compensate. Estuarine open water will increase more than 21 hectares. All freshwater and riverine habitats combined will decline by less than 2 hectares, and there will be a loss of 0.72 hectares of tidal swamp.

According to the model results it appears that whether or not developed dry land is protected, little impact on the gain or loss of freshwater and riverine categories or on irregularly flooded marsh and tidal swamps will occur. The categories most affected by protection of developed dry land will be transitional salt marsh and regularly flooded marsh. The increase in transitional salt marsh will be limited to only one-third of the amount created under the no-protection mode, and there will be 2.8 fewer hectares of new regularly flooded marsh created if developed dry land is protected.

Estimates of the predicted extent of each of the SLAMM categories under both protection scenarios in the years 2016, 2015, 2050, 2075, and 2100 in the Snow Creek estuary are provided in Table A-3 in Appendix A. Maps of the locations of existing (2016) and year 2100 wetland types are provided in Figures A7, A8, and A9 in Appendix A.

DISCUSSION AND CONCLUSIONS

The results of our simulations are estimates of the changes in size and location of coastal wetlands that will occur as a result of rising sea levels. It can be said with certainty that under the assumption that sea levels will rise 1.5 meters by the year 2100, coastal wetlands will decline. This is particularly true in places where protective measures are taken to block landward migration of wetlands. We cannot say with certainty that our estimates are accurate.

We ran our models in two different modes—protection and no protection—to obtain estimates of the impact that existing development will have on the ability of coastal wetlands to migrate landward. In reality, we will not see either 100% protection of developed lands or 100% of no protection in any of the estuaries. In the Duckabush, developed land immediately landward of current marshes is of low value, so the gain in value achieved by building dikes or berms will not likely justify the cost. Consequently we expect minimal effort to protect developed land in the Duckabush. In and around the Quilcene estuary much of the developed land is already elevated above the inundation levels expected in 2100, but it is likely that some alterations to the lower lying areas may be made to protect developed land. A similar situation occurs in the Snow Creek estuary. In either case we expect that some areas of developed land may be abandoned to the encroaching marshes, but most will continue to be protected.

The SLAMM is a mechanistic model. The results yield the best estimate in the absence of better data, but no more. All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the landward migration of wetlands, and simplifications of the system.

The erosion and accretion values we used as inputs were the best available. We did not have independent data to estimate some accretion or erosion rates, but simply used SLAMM defaults. If the accretion rates are overestimated or the erosion rates are underestimated, then landward migration could be greater.

The erosion values of 2.0 m/year for marshes and 1.0 m/year for swamps are SLAMM defaults. As the simulations were run, it was noticed that the erosion inputs likely overestimated marsh and swamp erosion. The SLAMM defaults are single-point averages estimated over a broad range of coastal conditions, including those adjacent to oceans and other environments with higher-energy wave action than in the estuaries we modeled. These estuaries are on inland waters where they are largely protected from high-energy waves. Consequently it is likely that erosion rates in our estuaries were overestimated. If so, then the landward migration of the marshes, tidal flat, and estuarine open water categories were also overestimated.

It is also suspected that the elevation data used to run simulations in the Quilcene estuary may have had some flaws. Suspected anomalies in the LiDAR layer resulted in the maps depicting a sharp-edged polygon of deep water in the tidal flats of Quilcene bay where deep estuarine open water was not expected (Figure A4 in Appendix A). The raw LiDar data do indicate that a depression of lower elevations exist there, but neither aerial photographs nor field experience confirm that the depression actually exists. It is suspected that the LiDAR equipment may have malfunctioned during the flyover when this extensive tidal flat was mapped. It has been suggested that the anomaly might also be an artifact of merging maps from two separate flight transects. The suspected error did not affect estimates of the location or extent of any swamps or marshes, but in future refinements of our SLAMM simulations we hope to diagnose and rectify the problem.

Furthermore, the predicted rise of sea level between 2016 and 2100, while representing the best available science at present, may change with additional future analysis of global climate changes. If the current rate of sea level rise is underestimated, then gains of new transitional salt marsh and regularly flooded marsh will be overestimated.

As noted above, incomplete knowledge about how the coastal system responds to increased inundation is also a source of uncertainty in the modeling effort. The science of the landward migration process is still in its infancy. Much is unknown about the marsh migration process and the driving factors that create successful transition onto upland areas. If our current understanding of landward marsh migration overestimates the establishment of new marshes, then inland areas may merely be converted to tidal flats and open water. Furthermore, the land cover database does not include information about the health of current coastal wetlands. It is possible that stressed or degraded wetlands will transition to tidal flat or open water more quickly than the model predicts.

An additional source of uncertainty in these predictions is use of this simple model. Despite the diversity of wetlands in these estuaries, the SLAMM required condensing all aquatic habitats into only 13 categories. We further limited ourselves by conceiving this simulation study as a pilot project. Consequently, the simulations were run with a minimum of inputs. The SLAMM has options for adding components or “modules” to account for the effects of impervious surfaces and soil saturation, subsidence and uplift, salinity, storm surges, and other influences on coastal marsh development. We chose in this pilot study to apply only the basic approach to simulations, based primarily on existing wetlands, elevation, slope, and the input parameters listed in table 2.

Furthermore, the SLAMM simulates coastal system responses only to currently existing patterns of development. At this time, it is uncertain how much new development will occur between now and 2100. Additionally, it is uncertain what measures may be taken to block sea water from moving inland. These unknowns also raise the level of uncertainty in the predictions presented here.

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Appendix A

Appendix A

Appendix A contains, for each of the estuaries modeled in this project, tables detailing predicted changes in the extent of coastal wetland types (SLAMM categories) and maps depicting the predicted changes. The tables list the extent of existing wetland categories (based on 2015-16 inventory data) and the predicted extents in years 2025, 2050, 2075, and 2100, under two scenarios: 1) under the assumption that developed dry land will not be protected from rising waters and 2) under the assumption that developed dry land will be protected. The tables also include summaries of change between 2106 and 2100, expressed in both hectares and percent.

The maps show the existing (2016) extent of coastal wetland categories and the predicted extent in 2100 in both the “no protection” and the “protection” scenarios.

The following legend applies to all maps in Appendix A:

Map Legend

Table A-1. Changes in Extent of SLAMM Categories in the Duckabush Estuary

Sea Level Scenario: 1.5 meter Sea Level Rise between 2016 and 2100. No Protection for Developed Dry Land

All area measures are in hectares

Total Hectares: 625

Year	SLR (meters)	Developed Dry Land	Undeveloped Dry Land	Swamp	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Inland Open Water	Estuarine Open Water	Irreg.-Flooded Marsh	Inland Shore	Tidal Swamp
2016	0.000	51.81	302.10	1.18	0.80	25.55	1.64	113.95	1.65	120.37	2.65	2.14	0.77
2025	0.071	51.81	302.00	1.17	0.24	26.28	1.64	113.75	1.65	120.56	2.59	2.14	0.77
2050	0.408	51.68	301.46	1.12	0.47	26.99	1.63	105.35	1.51	129.29	2.19	2.14	0.77
2075	0.842	50.10	299.84	0.64	3.04	23.42	1.63	104.92	1.37	135.08	1.66	2.14	0.76
2100	1.295	47.98	297.45	0.18	4.20	19.59	1.63	109.47	1.05	139.22	0.96	2.14	0.74
CHANGE (hectares)		-3.83	-4.65	-1.00	3.39	-5.96	-0.01	-4.48	-0.60	18.85	-1.69	0.00	-0.03
CHANGE (percent)		-7.40	-1.54	-84.92	421.44	-23.32	-0.65	-3.93	-36.30	15.66	-63.91	0.00	-3.34

Sea Level Scenario: 1.5 meter Sea Level Rise between 2016 and 2100. Protection for Developed Dry Land

All area measures are in hectares

Total Hectares: 625

Year	SLR (meters)	Developed Dry Land	Undeveloped Dry Land	Swamp	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Inland Open Water	Estuarine Open Water	Irreg.-Flooded Marsh	Inland Shore	Tidal Swamp
2016	0.00	51.85	302.10	1.18	0.79	25.54	1.64	113.95	1.65	120.37	2.65	2.14	0.77
2025	0.07	51.85	302.00	1.17	0.24	26.24	1.64	113.75	1.65	120.56	2.59	2.14	0.77
2050	0.41	51.85	301.46	1.12	0.40	26.90	1.63	105.35	1.51	129.29	2.19	2.14	0.77
2075	0.84	51.85	299.84	0.64	1.62	23.08	1.63	104.92	1.37	135.08	1.66	2.14	0.76
2100	1.29	51.85	297.45	0.18	2.28	17.66	1.63	109.46	1.05	139.22	0.96	2.14	0.74
CHANGE (hectares)		0	-4.65	-1.00	1.49	-7.88	-0.01	-4.49	-0.60	18.85	-1.69	0.00	-0.03
CHANGE (percent)		0	-1.54	-84.92	189.94	-30.86	-0.65	-3.94	-36.30	15.66	-63.91	0.00	-3.34

Figure A-1. Duckabush Estuary. Extent of coastal wetland types in year 2016.

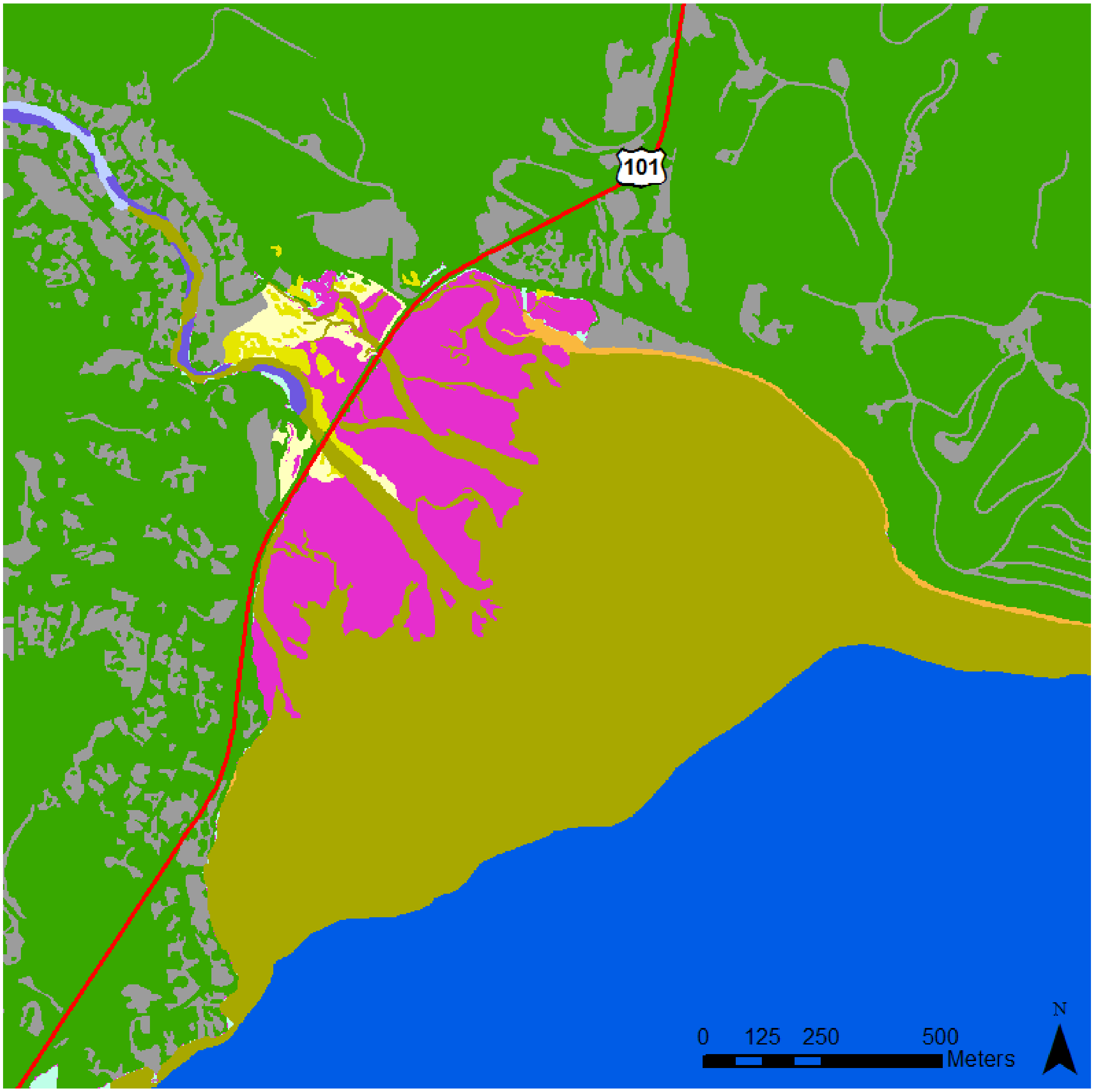

Figure A-2. Duckabush Estuary. Extent of coastal wetland types in year 2100. No protection for developed dry land. Sea level scenario: 1.5 meter sea level rise by 2100.

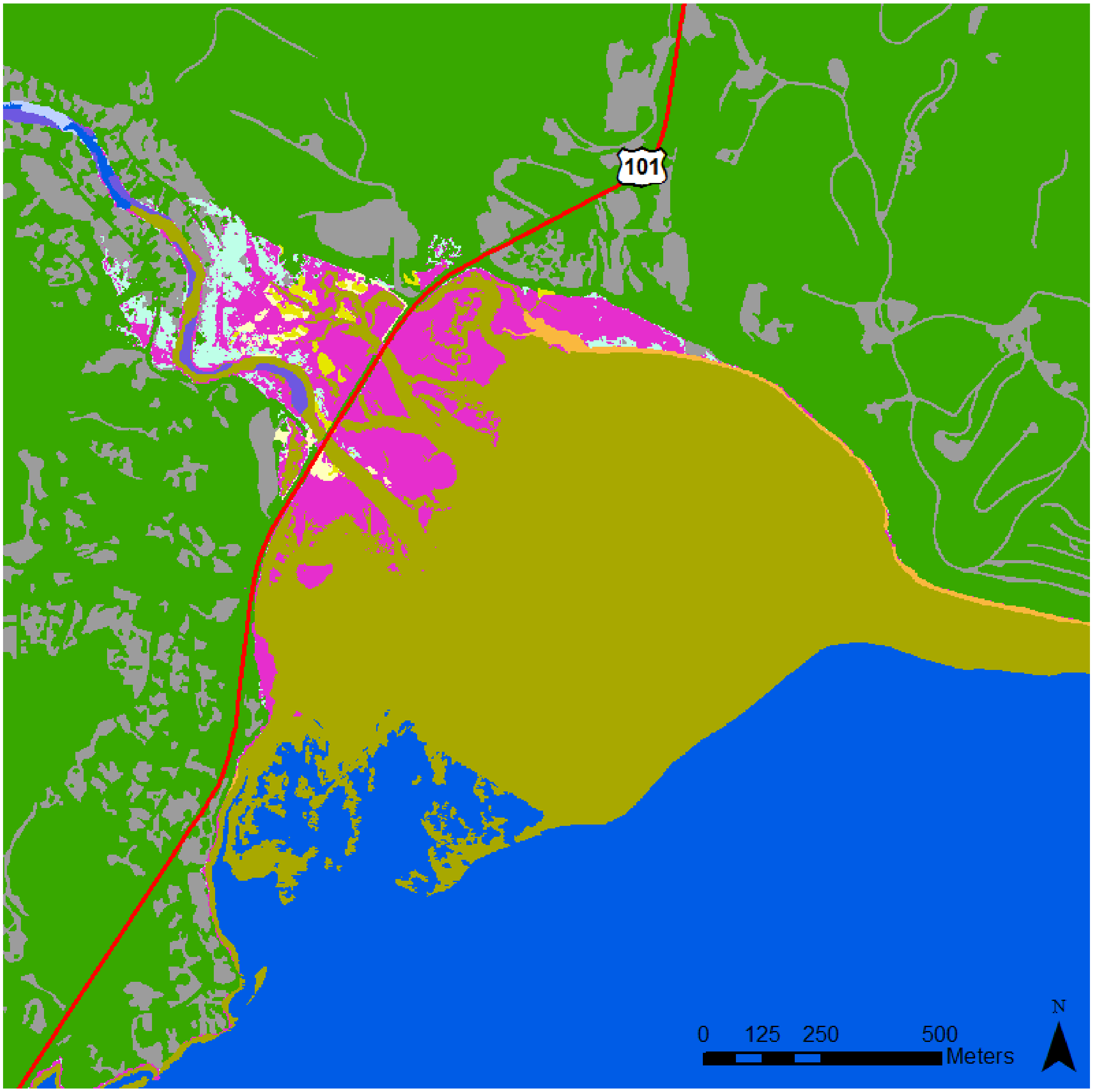

Figure A-3. Duckabush Estuary. Extent of coastal wetland types in year 2100. Protection for developed dry land. Sea level scenario: 1.5 meter sea level rise by 2100.

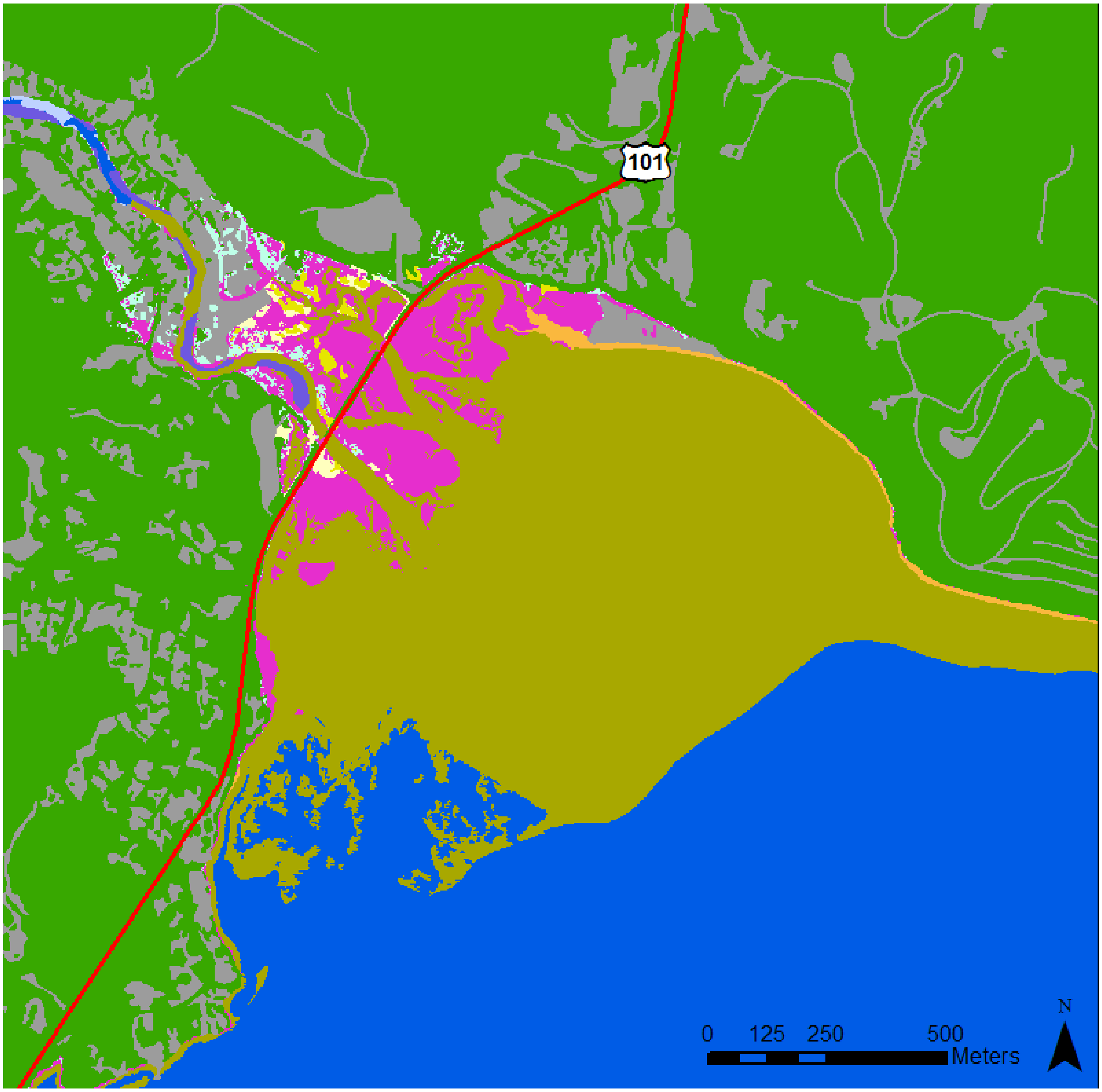

Table A-2. Changes in Extent of SLAMM Categories in the Quilcene Estuary

Sea Level Scenario: 1.5 meter Sea Level Rise between 2016 and 2100. No protection for Developed Dry Land

All area measures are in hectares

Total Hectares 782

Year	SLR (meters)	Developed Dry Land	Undeveloped Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Inland Open Water	Riverine Tidal	Estuarine Open Water	Irreg.-Flooded Marsh	Tidal Swamp
2016	0.00	55.65	329.05	19.33	15.69	15.76	0.69	59.54	2.91	234.51	2.98	4.23	31.46	8.99	0.88
2025	0.07	55.64	328.99	19.30	15.68	15.76	0.24	60.16	2.90	234.01	2.92	4.23	32.04	8.93	0.88
2050	0.41	55.42	327.15	18.76	12.93	15.76	4.48	61.05	2.88	233.00	2.57	3.51	34.96	8.33	0.88
2075	0.84	54.10	321.13	14.24	9.50	15.73	13.40	59.39	2.87	240.83	2.20	1.77	39.85	5.80	0.88
2100	1.29	50.19	310.93	8.11	6.80	15.58	20.62	59.40	2.86	256.00	1.82	0.92	44.64	2.95	0.87
CHANGE (hectares)		-5.46	-18.13	-11.22	-8.88	-0.19	19.93	-0.14	-0.05	21.49	-1.16	-3.31	13.18	-6.04	-0.01
CHANGE (percent)		-9.82	-5.51	-58.04	-56.63	-1.17	2889.75	-0.24	-1.81	9.16	-38.84	-78.26	41.88	-67.20	-1.35

Sea Level Scenario: 1.5 meter Sea Level Rise between 2016 and 2100. Protection for Developed Dry Land

All area measures are in hectares

Total Hectares 782

Year	SLR (meters)	Developed Dry Land	Undeveloped Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Inland Open Water	Riverine Tidal	Estuarine Open Water	Irreg.-Flooded Marsh	Tidal Swamp
2016	0.00	55.67	328.98	19.33	15.69	15.76	0.64	59.53	2.91	234.57	2.98	4.23	31.46	8.99	0.88
2025	0.07	55.67	328.91	19.30	15.68	15.76	0.24	60.09	2.90	234.01	2.92	4.23	32.10	8.93	0.88
2050	0.41	55.67	327.09	18.76	12.93	15.76	4.34	60.89	2.88	232.86	2.57	3.51	35.16	8.33	0.88
2075	0.84	55.67	321.07	14.24	9.50	15.73	12.23	58.96	2.86	240.56	2.20	1.77	40.15	5.80	0.88
2100	1.29	55.67	310.89	8.11	6.80	15.58	17.03	57.47	2.85	255.62	1.82	0.92	45.05	2.95	0.87
CHANGE (hectares)		0	-18.09	-11.22	-8.88	-0.19	16.38	-2.06	-0.06	21.06	-1.16	-3.31	13.58	-6.04	-0.01
CHANGE (percent)		0	-5.50	-58.04	-56.63	-1.17	2540.30	-3.46	-2.15	8.98	-38.84	-78.26	43.17	-67.20	-1.35

Figure A-4. Quilcene Estuary. Extent of coastal wetland types in year 2016.

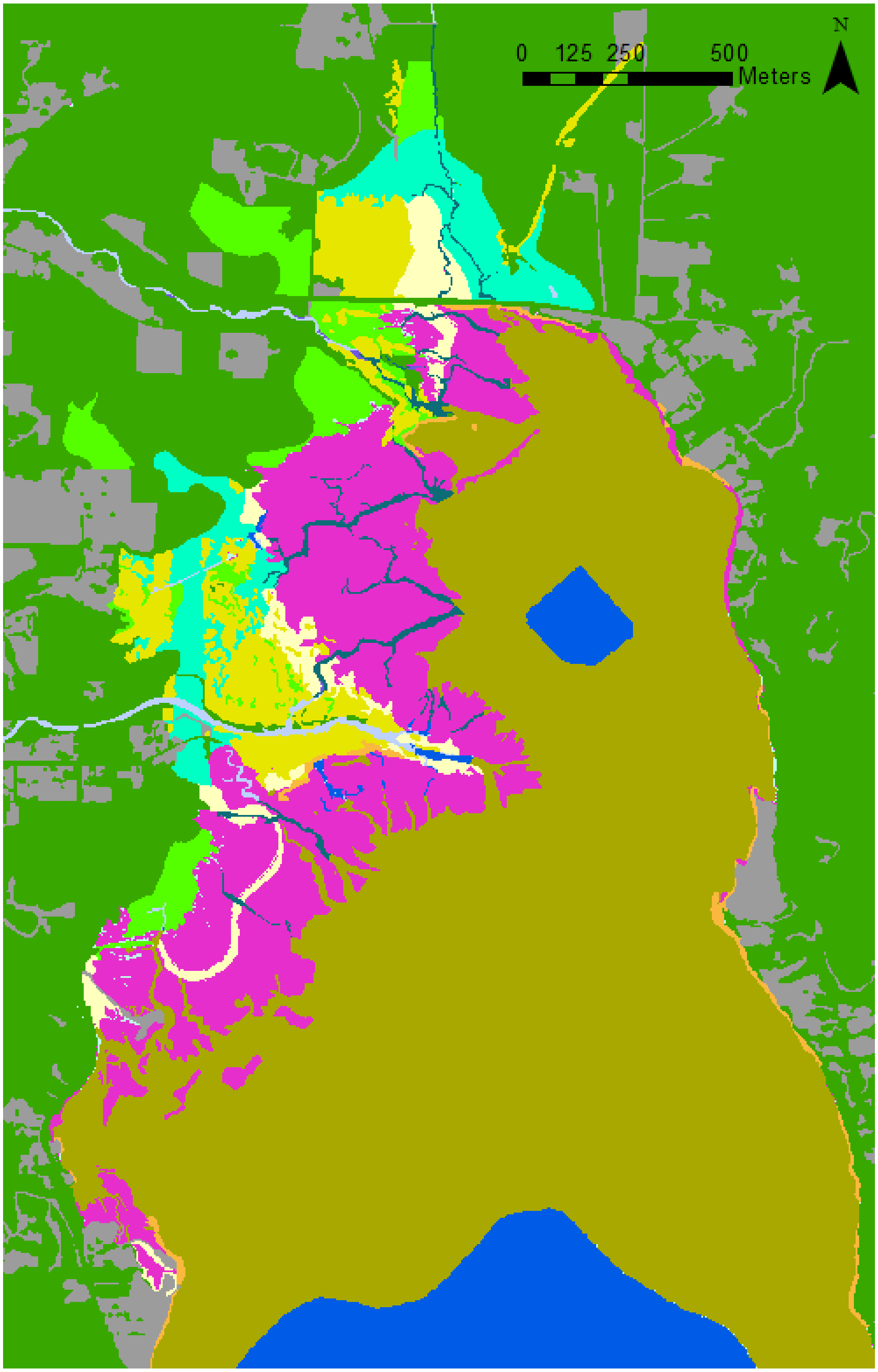

Figure A-5. Quilcene Estuary. Extent of coastal wetland types in year 2100. No protection for developed dry land. Sea level scenario: 1.5 meter sea level rise by 2100.

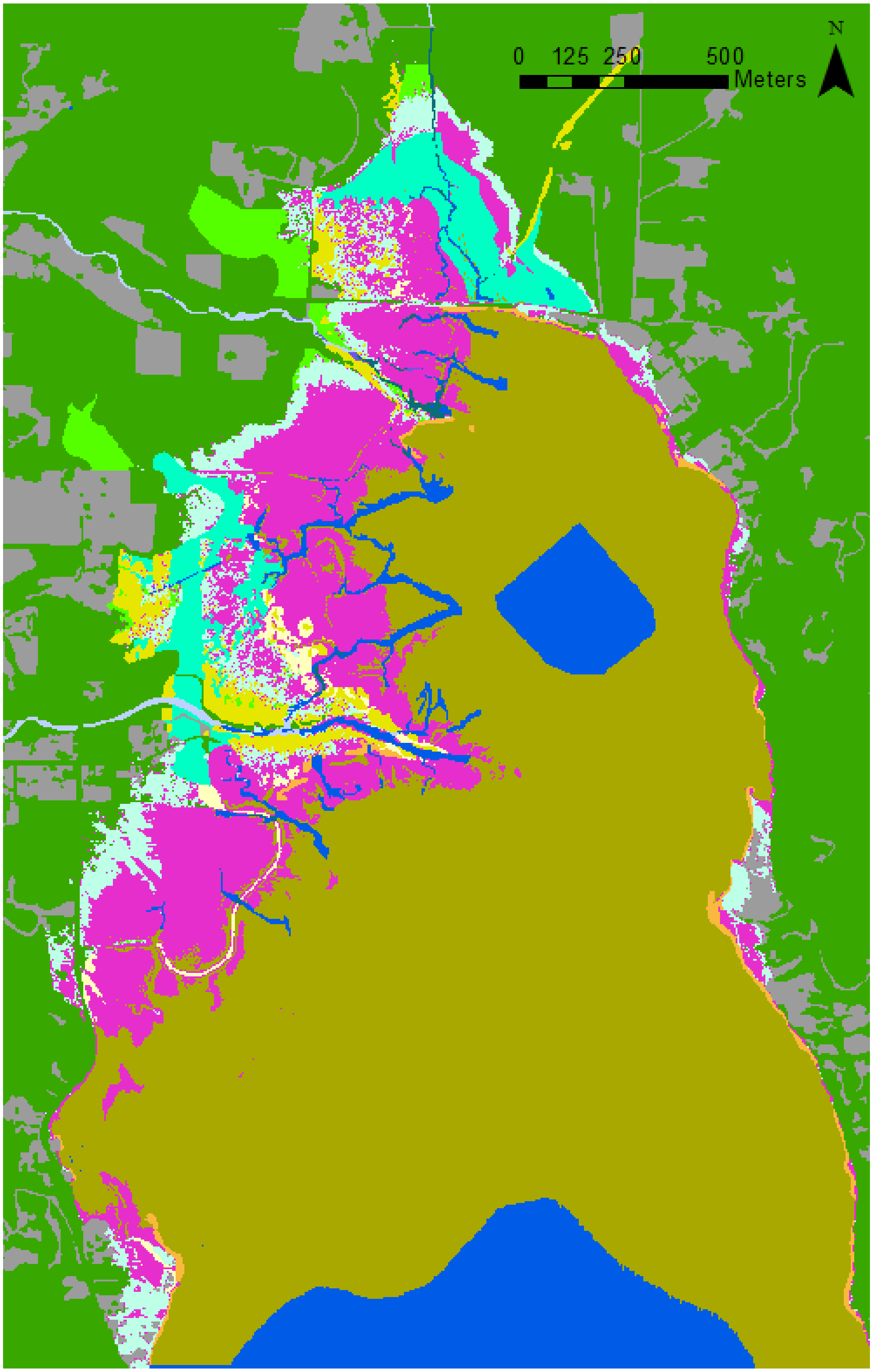

Figure A-6. Quilcene Estuary. Extent of coastal wetland types in year 2100. Protection for developed dry land. Sea level scenario: 1.5 meter sea level rise by 2100.

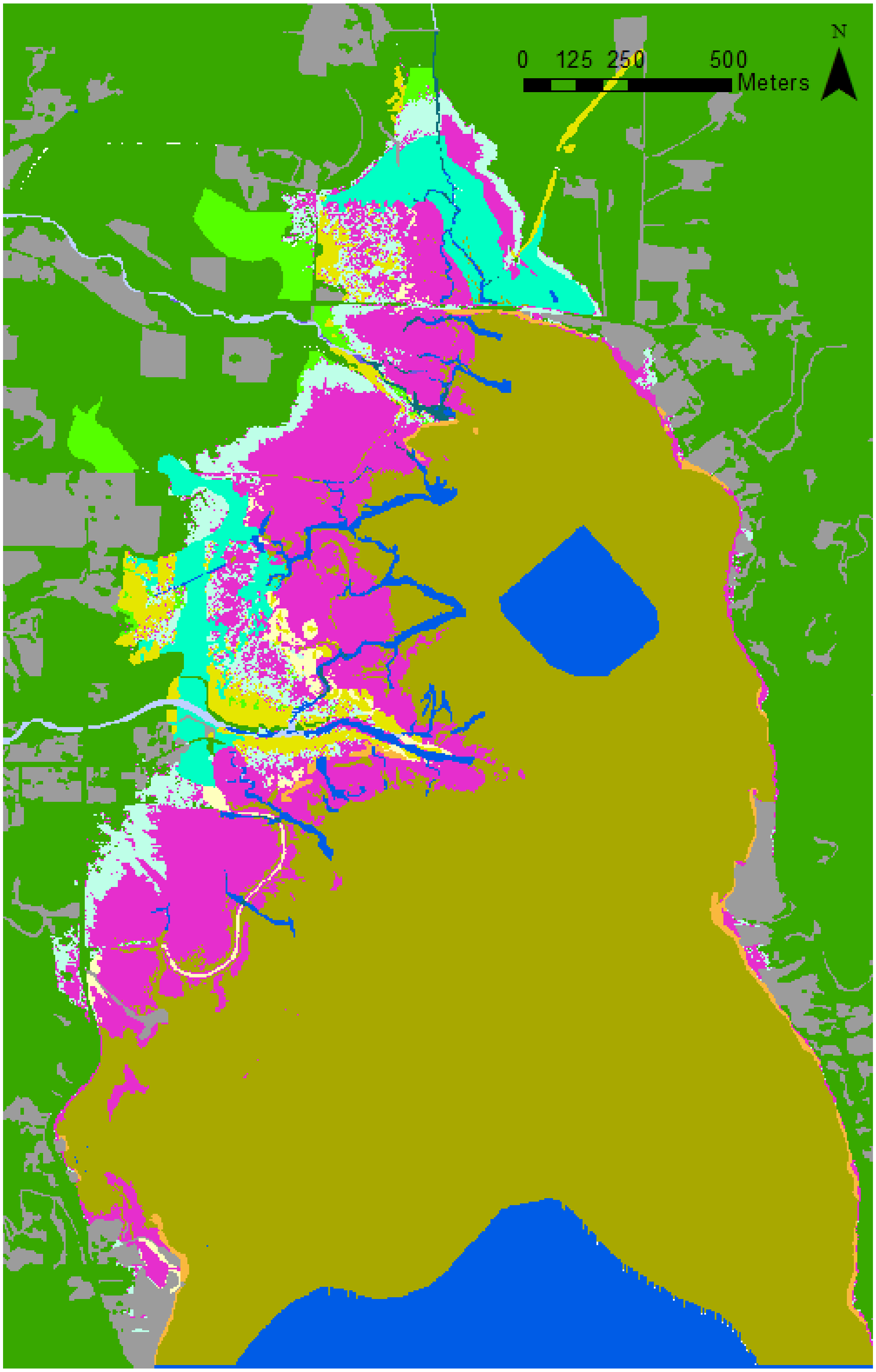

Table A-3. Changes in Extent of SLAMM Categories in the Snow-Salmon Creek Estuary

Sea Level Scenario: 1.5 meter Sea Level Rise between 2016 and 2100. No protection for Developed Dry Land

All area measures are in Hectares

Total Hectares 624

Year	SLR (meters)	Developed Dry Land	Undeveloped Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Inland Open Water	Riverine Tidal	Estuarine Open Water	Irreg.-Flooded Marsh	Tidal Swamp
2016	0.00	20.38	433.66	1.63	2.30	0.55	4.33	12.87	0.68	56.34	1.12	0.41	86.51	0.71	2.02
2025	0.07	20.25	433.52	1.60	2.29	0.55	2.59	14.93	0.68	55.96	1.10	0.40	86.93	0.69	2.02
2050	0.41	19.50	431.58	1.44	2.13	0.55	3.27	16.50	0.68	48.09	0.98	0.36	95.80	0.61	2.00
2075	0.84	18.33	426.33	1.27	1.79	0.55	6.16	18.54	0.67	45.46	0.85	0.31	100.97	0.41	1.86
2100	1.29	16.75	421.45	1.19	1.44	0.55	5.96	17.93	0.60	46.87	0.80	0.15	107.84	0.67	1.30
CHANGE (hectares)		-3.63	-12.20	-0.44	-0.86	0.00	1.63	5.05	-0.08	-9.47	-0.33	-0.26	21.34	-0.03	-0.72
CHANGE (percent)		-17.80	-2.81	-26.99	-37.46	0.00	37.75	39.25	-12.20	-16.81	-29.04	-62.91	24.67	-4.75	-35.66

Sea Level Scenario: 1.5 meter Sea Level Rise between 2016 and 2100. Protection for Developed Dry Land

All area measurements are in Hectares

Total Hectares 624

Year	SLR (meters)	Developed Dry Land	Undeveloped Dry Land	Swamp	Inland-Fresh Marsh	Tidal-Fresh Marsh	Trans. Salt Marsh	Regularly-Flooded Marsh	Estuarine Beach	Tidal Flat	Inland Open Water	Riverine Tidal	Estuarine Open Water	Irreg.-Flooded Marsh	Tidal Swamp
2016	0.00	20.72	433.66	1.63	2.30	0.55	4.01	12.85	0.68	56.34	1.12	0.41	86.51	0.71	2.02
2025	0.07	20.72	433.52	1.60	2.29	0.55	2.36	14.69	0.68	55.96	1.10	0.40	86.93	0.69	2.02
2050	0.41	20.72	431.58	1.44	2.13	0.55	2.59	16.01	0.68	48.07	0.98	0.36	95.78	0.61	2.00
2075	0.84	20.72	426.33	1.27	1.79	0.55	5.13	17.30	0.67	45.39	0.85	0.31	100.91	0.41	1.86
2100	1.29	20.72	421.45	1.19	1.44	0.55	4.58	15.55	0.60	46.77	0.80	0.15	107.74	0.67	1.30
CHANGE (hectares)		0	-12.20	-0.44	-0.86	0.00	0.57	2.70	-0.08	-9.57	-0.33	-0.26	21.23	-0.03	-0.72
CHANGE (percent)		0	-2.81	-26.99	-37.46	0.00	14.11	20.99	-12.20	-16.99	-29.04	-62.91	24.55	-4.75	-35.66

Figure A-7. Snow-Salmon Creek Estuary. Extent of coastal wetland types in year 2016.

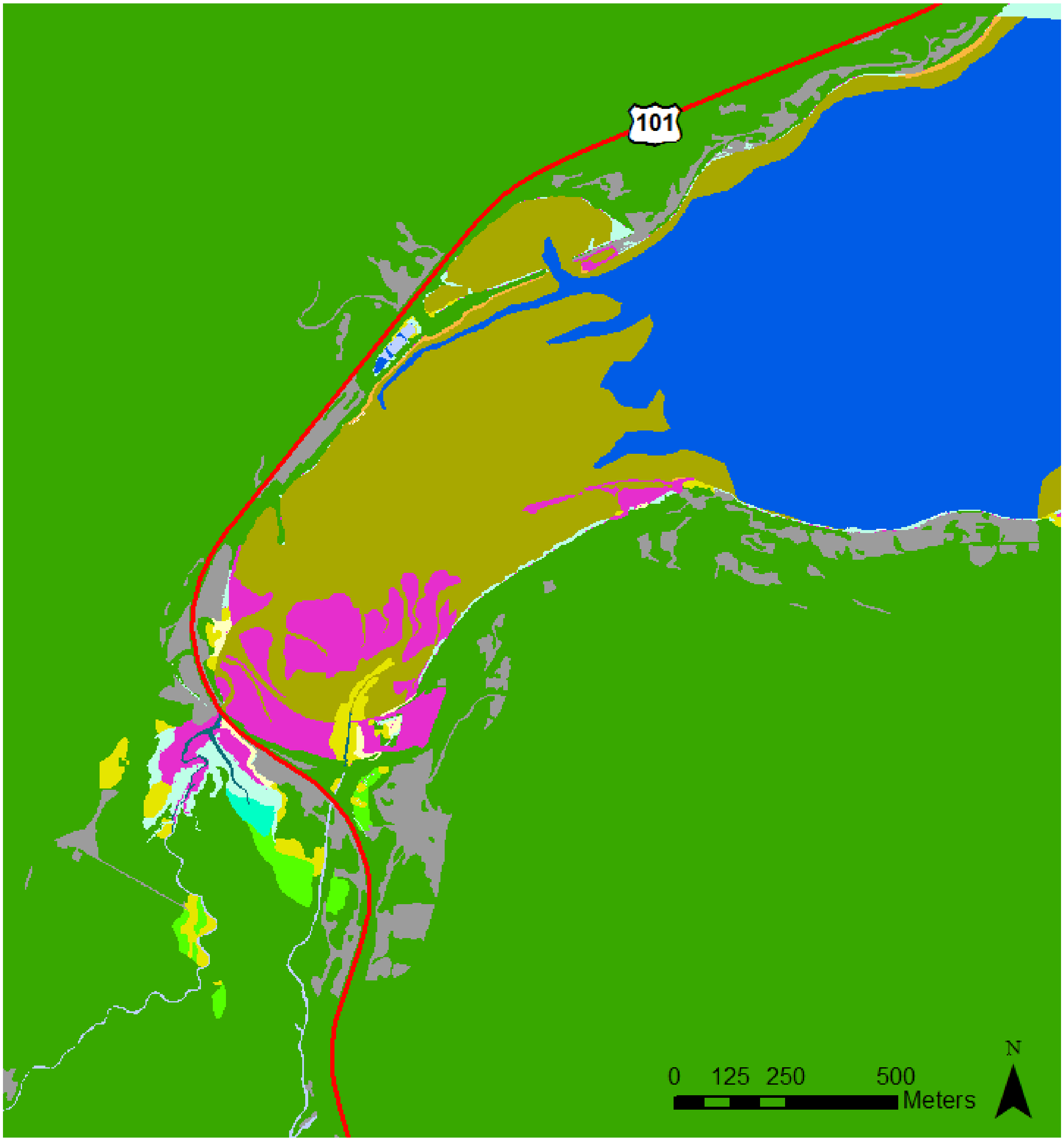

Figure A-8. Snow-Salmon Creek Estuary. Extent of coastal wetland types in year 2100. No protection for developed dry land. Sea level scenario: 1.5 meter sea level rise by 2100.

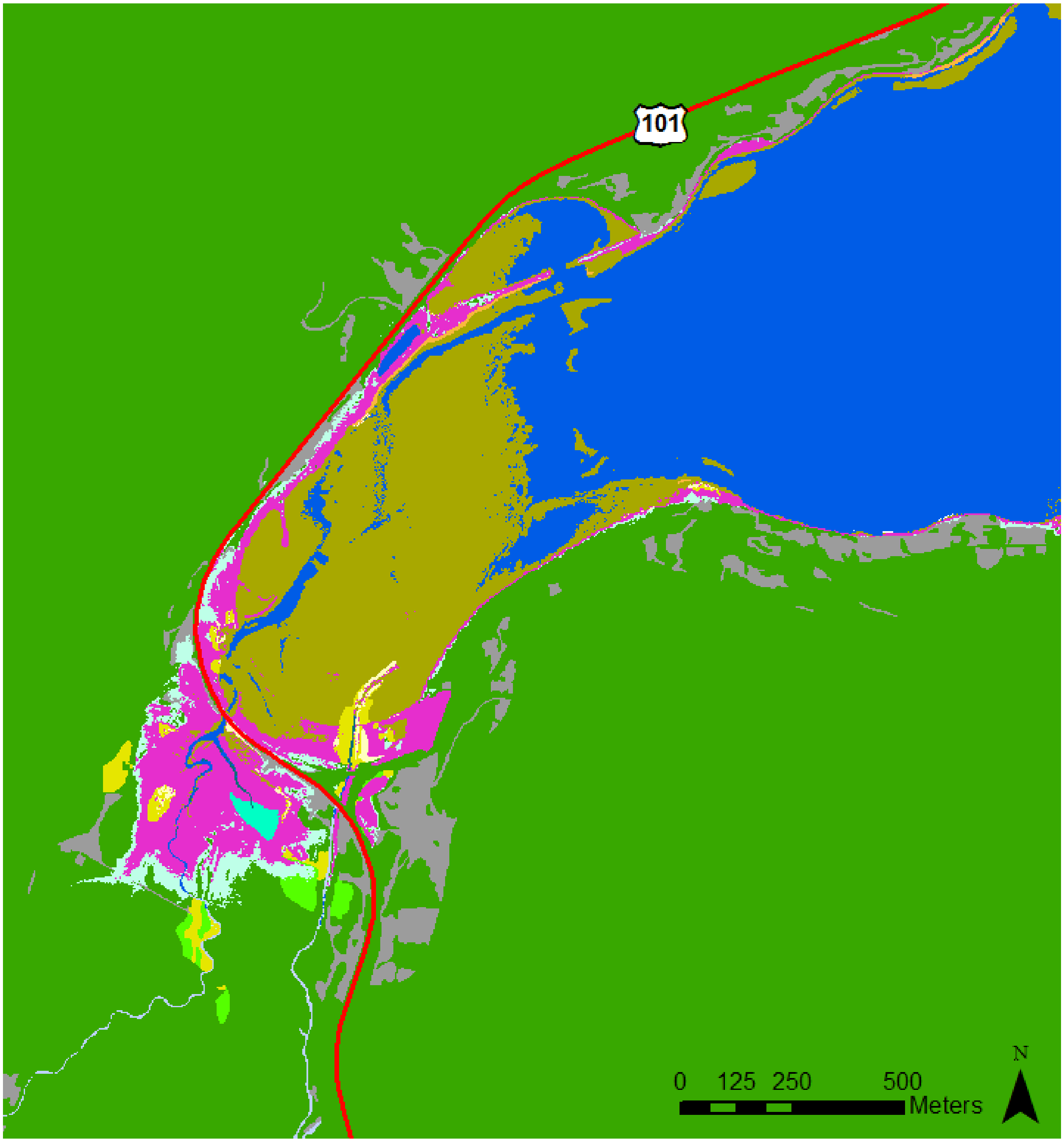

Figure A-9. Snow-Salmon Creek Estuary. Extent of coastal wetland types in year 2100. Protection for developed dry land. Sea level scenario: 1.5 meter sea level rise by 2100.