Updated Application of the Sea-Level Affecting Marshes Model (SLAMM 6) to J.N. “Ding” Darling NWR

Includes application of the Roads and Infrastructure Module

U. S. Fish and Wildlife Service
National Wildlife Refuge System
Division of Natural Resources and Conservation Planning
Conservation Biology Program
4401 N. Fairfax Drive - MS 670
Arlington, VA 22203

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warren pinnacle consulting, inc.
PO Box 315, Waitsfield VT, 05673
(802)-496-3476

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Introduction

Tidal marshes are among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR). The Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) suggested that global sea level will increase by approximately 30 cm to 100 cm by 2100 (IPCC 2001). Rahmstorf (2007) suggests that this range may be too conservative and that the feasible range by 2100 is 50 to 140 cm. Rising sea levels may result in tidal marsh submergence (Moorhead and Brinson 1995) and habitat "migration" as salt marshes transgress landward and replace tidal freshwater and irregularly-flooded marsh (Park et al. 1991).

In an effort to plan for and potentially mitigate the effects of sea-level rise on the U.S. National Wildlife Refuge System (Refuge System), the U. S. Fish and Wildlife Service (FWS) uses a variety of analytical approaches, most notably the SLAMM model. FWS conducts some SLAMM analysis in-house and, more commonly, contracts the application of the SLAMM model. In most cases Refuge System SLAMM analyses are designed to assist in the development of comprehensive conservation plans (CCPs), land acquisition plans, habitat management plans, and other land and resource management plans.

This is the second application of SLAMM to J.N. "Ding" Darling NWR. The first application of SLAMM to the refuge, carried out in 2009, did not include LiDAR-derived elevation data and elevations were dirved from a 1974 contour map. The current application uses a bare-earth LiDAR elevation data obtained in 2010 and a wetland layer derived from aerial photos taken in 1999.

Model Summary

Changes in tidal marsh area and habitat type in response to sea-level rise were modeled using the Sea Level Affecting Marshes Model (SLAMM 6) that accounts for the dominant processes involved in wetland conversion and shoreline modifications during long-term sea level rise (Park et al. 1989; www.warrenpinnacle.com/prof/SLAMM).

Successive versions of the model have been used to estimate the impacts of sea level rise on the coasts of the U.S. (Titus et al. 1991; Lee et al. 1992; Park et al. 1993; Galbraith et al. 2002; National Wildlife Federation & Florida Wildlife Federation 2006; Glick et al. 2007; Craft et al. 2009).

Within SLAMM, there are five primary processes that affect wetland fate under different scenarios of sea-level rise:

- **Inundation:** The rise of water levels and the salt boundary are tracked by reducing elevations of each cell as sea levels rise, thus keeping mean tide level (MTL) constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell.
- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the marsh to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site- specific data.

- **Overwash:** Barrier islands of under 500 meters (m) width are assumed to undergo overwash during each specified interval for large storms. Beach migration and transport of sediments are calculated.
- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the fresh water table to rising sea level close to the coast.
- **Accretion:** Sea level rise is offset by sedimentation and vertical accretion using average or site-specific values for each wetland category. Accretion rates may be spatially variable within a given model domain and can be specified to respond to feedbacks such as frequency of flooding.

SLAMM Version 6.0 was developed in 2008/2009 and is based on SLAMM 5. SLAMM 6.0 provides backwards compatibility to SLAMM 5, that is, SLAMM 5 results can be replicated in SLAMM 6. However, SLAMM 6 also provides several optional capabilities.

- Accretion Feedback Component: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified. This feedback is used where adequate data exist for parameterization.
- Salinity Model: Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity. This optional sub-model is not utilized in USFWS simulations.
- Integrated Elevation Analysis: SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. This functionality is used in USFWS simulations to test the SLAMM conceptual model at each site. The causes of any discrepancies are then tracked down and reported on within the model application report.
- Flexible Elevation Ranges for land categories: If site-specific data indicate that wetland elevation ranges are outside of SLAMM defaults, a different range may be specified within the interface. In USFWS simulations, the use of values outside of SLAMM defaults is rarely utilized. If such a change is made, the change and the reason for it are fully documented within the model application reports.
- Many other graphic user interface and memory management improvements are also part of the new version including an updated *Technical Documentation*, and context sensitive help files.

Road Inundation Module. SLAMM 6 has recently been updated with an infrastructure module that integrates roads layers into an existing SLAMM simulation. This infrastructure has two effects on SLAMM simulations. First, SLAMM can now predict the vulnerability of road infrastructure with respect to sea-level rise. Second, the effects of road elevations on wetland projections and water paths are accounted for in wetland-fate predictions.

SLAMM accounts for road lengths within in each cell containing a portion of the road and includes separate road-specific elevations within each cell. The heights of 30-, 60-, and 90-day inundations are input parameters based on data from local tide gages. During the simulation, SLAMM searches for water inundation pathways using the connectivity algorithm to estimate how frequently each segment of road will be inundated. At the end of a SLAMM simulation road maps are produced and numerical data describing the total length of roads that are inundated are summarized into the following categories

- km of roads inundated more frequently than every 30 days (highly vulnerable)

- km of roads inundated once each 30-60 day period
- km of roads inundated once each 60-90 day period and
- km of roads inundated less frequently than once each 90 days (rarely flooded)

For Ding Darling NWR, these data are summarized in the report below.

For a thorough accounting of SLAMM model processes and the underlying assumptions and equations, please see the SLAMM 6.0 *Technical Documentation* (Clough et al. 2010). This document is available at http://warrenpinnacle.com/prof/SLAMM

All model results are subject to uncertainty due to limitations in input data, incomplete knowledge about factors that control the behavior of the system being modeled, and simplifications of the system (Council for Regulatory Environmental Modeling 2008). Site-specific factors that increase or decrease model uncertainty may be covered in the *Discussion* section of this report.

Sea Level Rise Scenarios

Some SLAMM 6 predictions are obtained using SLR estimates from the Special Report on Emissions Scenarios (SRES) published by the Intergovernmental Panel on Climate Change (IPCC). All IPCC scenarios describe futures that are generally more affluent than today and span a wide range of future levels of economic activity, with gross world product rising to 10 times today's values by 2100 in the lowest, to 26-fold in the highest scenarios (IPCC 2007). Among the IPCC families of scenarios, two approaches were used, one that made harmonized assumptions about global population, economic growth, and final energy use, and those with an alternative approach to quantification. This is important to keep in mind as not all of the IPCC scenarios share common assumptions regarding the driving forces of climate change.

In this model application, the A1B scenario mean and maximum predictions are applied. Important assumptions were made in this scenario: reduction in the dispersion of income levels across economies (i.e. economic convergence), capacity building, increased cultural and social interactions among nations, and a substantial reduction in regional differences in per capita income, primarily from the economic growth of nations with increasing income (Nakicenovic et al. 2000). In addition, the A1 family of scenarios assumes that the future world includes rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Given today's global economic and political climate, as well as environmental and ecological constraints, these may not be feasible assumptions for the future.

In particular, the A1B scenario assumes that energy sources will be balanced across all sources, with an increase in use of renewable energy sources coupled with a reduced reliance on fossil fuels (Nakicenovic et al. 2000). Given this A1B scenario, the IPCC WGI Fourth Assessment Report (IPCC 2007) suggests a likely range of 0.21 m to 0.48 m of SLR by 2090-2099 "excluding future rapid dynamical changes in ice flow." The IPCC-produced A1B-mean scenario that was run as a part of this project falls near the middle of this estimated range, predicting 0.39 m of global SLR by 2100. A1B-maximum predicts 0.69 m of global SLR by 2100. However, other scientists using the same set of economic growth scenarios have produced much higher estimates of SLR as discussed below.

Recent literature (Chen et al. 2006; Monaghan et al. 2006) indicates that eustatic sea level rise is progressing more rapidly than was previously assumed. This underestimation may be due to the dynamic changes in ice flow omitted within the IPCC report's calculations, and a consequence of overestimating the possibilities for future reductions in greenhouse gas emissions while concurrently striving for economic growth.

A recent paper in the journal *Science* (Rahmstorf 2007) suggests that, taking into account possible model error, a feasible range of 50 to 140 cm by 2100. This work was recently updated and the ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf 2009). Pfeffer et al. (2008) suggests that 2 m by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions. A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected SLRs for the end of the 21st century are too low" (Clark 2009). A recent paper by Grinsted et al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario…" Grinsted also states that there is a "low probability" that SLR will match the lower IPCC estimates.

The variability of SLR predictions presented in the scientific literature illustrates the significant amount of uncertainty in estimating future SLR. Much of the uncertainty may be due to the unknown future of the drivers climate change, such as fossil fuel consumption and the scale of human enterprise. In order to account for these uncertainties, and to better reflect these uncertainties as well as recently published peer-reviewed measurements and projections of SLR as noted above, SLAMM was run not only assuming A1B-mean and A1B-maximum SLR scenarios, but also for 1 m, 1.5 m, and 2 m of eustatic SLR by the year 2100 as shown in Figure 1.

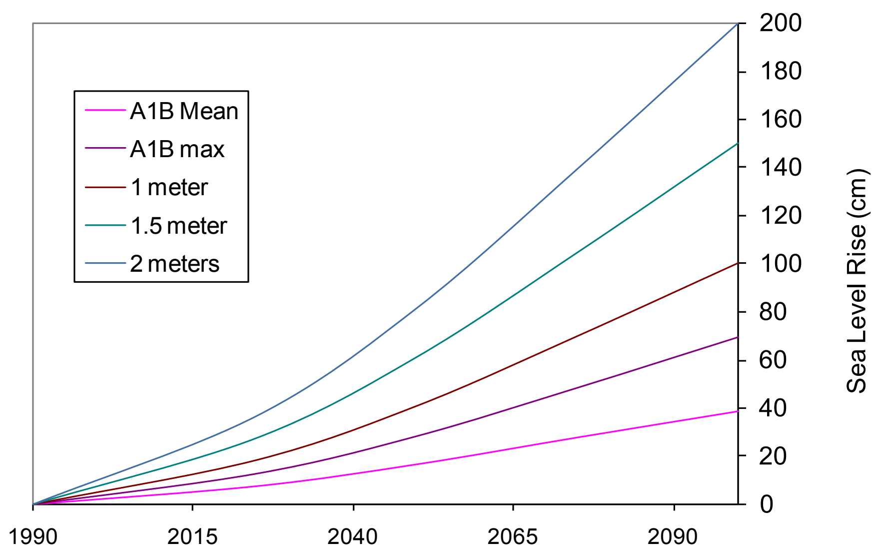


Figure 1. Summary of SLR scenarios utilized.

Data Sources and Methods

This modeling analysis updates the 2011 analysis of Ding Darling NWR with the best-available wetland and elevation coverages, and also applies the SLAMM roads module as part of the analysis. In addition, the cell-size was reduced from 30 meters to 5 meters.

Wetland layer. Figure 2 shows the most recent available wetland layer derived from a NWI survey dated 2008. Converting the surveys into 5 m x 5 m cells indicated that the approximately 8,100 acres. J.N. "Ding" Darling NWR (approved acquisition boundary including water) is composed of the following categories:

Land cover type		Area (acres)	Percentage (%)
	Mangrove	3101	38
	Tidal Flat	1699	21
	Swamp	1329	16
	Estuarine Open Water	950	12
	Undeveloped Dry Land	742	9
	Inland Fresh Marsh	84	1
	Estuarine Beach	59	<1
	Developed Dry Land	56	<1
	Inland Open Water	35	<1
	Ocean Beach	29	<1
	Open Ocean	6	<1
	Regularly Flooded Marsh	6	<1
	Inland Shore	5	<1
	Tidal Swamp	1	<1
	Total (incl. water)	**8103**	**100**

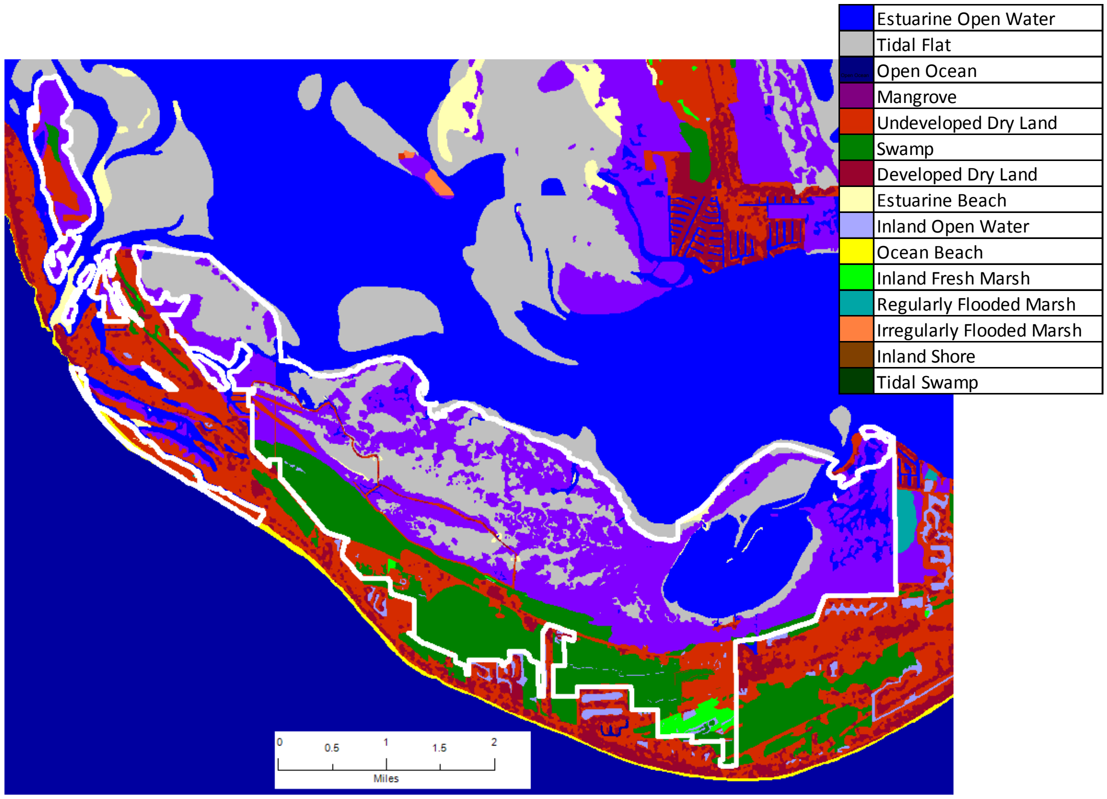


Figure 2. NWI coverage of the study area. Approved refuge boundaries are indicated in white.

Elevation Data. The elevation layer covering the refuge area is based on bare-earth LiDAR data collected in 2007 for FEMA, downloaded from the National Elevation Dataset, and 2010 LiDAR data collected for NOAA by the USACE (Figure 3 below shows the covered areas).

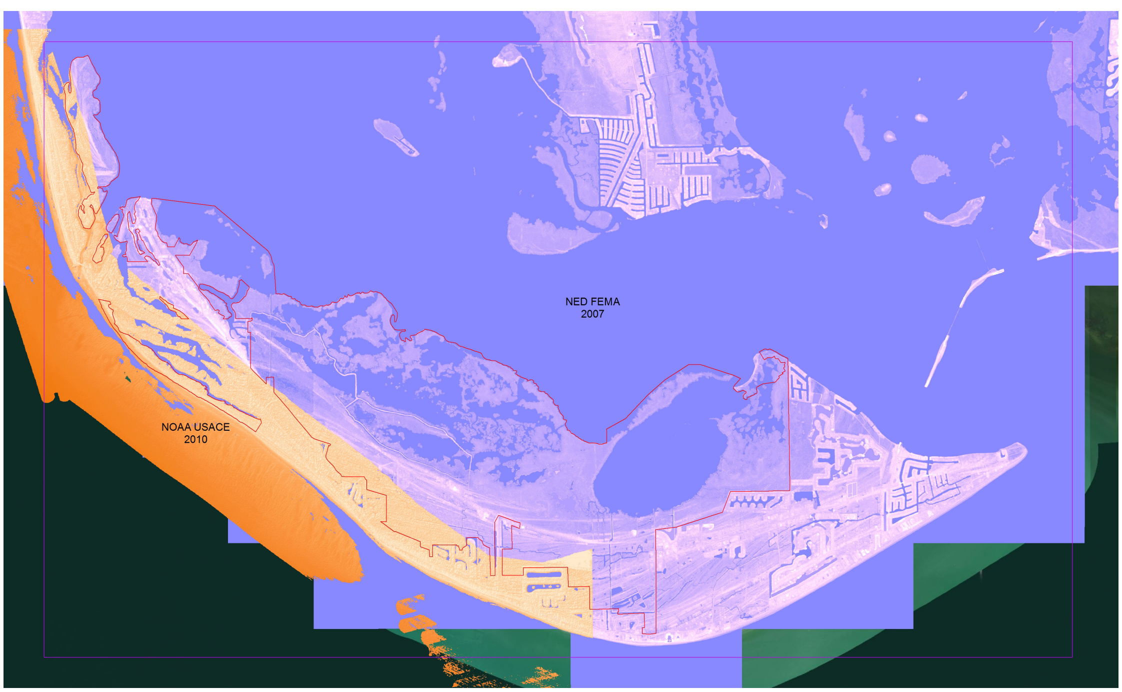


Figure 3. Elevation data coverage of the study area. In orange is the area covered by 2010 NOAA USACE data while in purple the 2007 NED FEMA data.

Dikes and Impoundments. According to the National Wetland Inventory, there are no areas protected by dikes or impoundments. However, the connectivity algorithm was used in this simulation to capture the effects of any natural or man-made impoundments that may not have been marked as diked in the National Wetland Inventory. The connectivity module of SLAMM ensures that dry land only converts to wetland if there is an unimpeded path from open water to the dry land in question.

Roads. The road data considered within the study area were gathered from multiple sources: the Road Inventory Program (RIP), the ESRI Roads Layer, and some roads were manually drawn as they were observed in the LiDAR layer and satellite imagery. The overall road layer is shown in Figure 4. Road elevations were independently extracted from the LiDAR data using a buffer area centered on the roads. In this way, the assigned elevations of cells containing roads reflect the observed elevation of the roads rather than the average of elevations measured in the entire area covered by the cell.

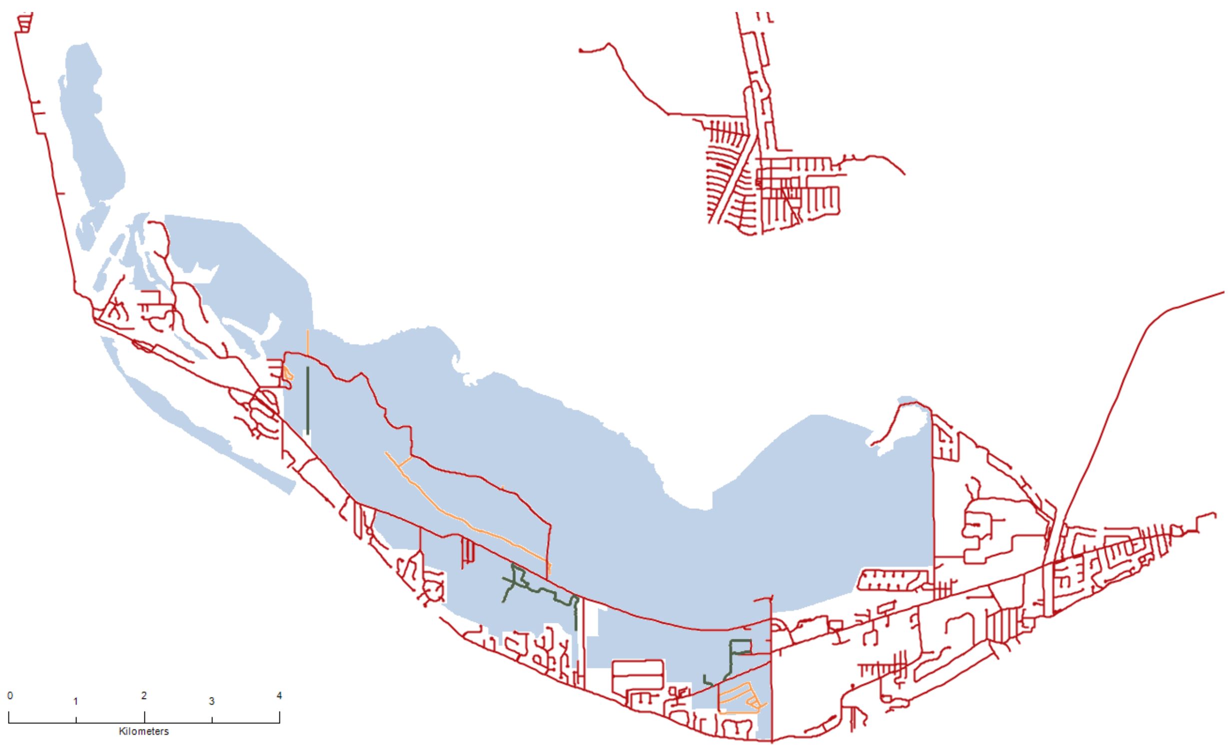


Figure 4. Roads around the study area at Ding Darling NWR.
Red lines are from an ESRI Roads layer; Orange lines reflect the cycle 4 GIS (Road Inventory Program).
Grey lines are roads manually drawn based on the elevation layer; The blue area represents the approved acquisition boundary.

Historic sea level rise rates. The historic trend for relative sea level rise rate applied is 2.4 mm/yr, the average value measured Fort Myers, FL (NOAA gauge # 8725520). This rate is somewhat higher than the global (eustatic) SLR for the last 100 years (approximately 1.7 mm/yr), potentially indicating minor subsidence in the region or some other factor causing SLR to be higher than the global average.

Tide Ranges. Tidal parameters were obtained the local NOAA gauges shown in Table 1. Given this spatial variability, two input subsites were identified as shown in Figure 6.

Table 1. NOAA gauges used

NOAA Gauge Name	NOAA Station ID	GT (m)
Matanzas Pass Estero Island	8725366	0.794
Estero Island Estero Bay	8725351	0.769
Hurricane Bay San Carlos Island	8725368	0.794
Tarpon Bay	8725362	0.693
Punta Rassa	8725391	0.689
Ostego Bay	8725331	0.758
Estero River Estero Bay	8725346	0.747
Coconut Point Estero Bay	8725319	0.755
Port Boca Grande Charlotte Hbr	8725577	0.475
Bokellia	8725541	0.526
Englewood Lemon Bay	8725747	0.534
Pine Island	8725528	0.517
North Captiva Island	8725488	0.606
Manasota	8725809	0.512
Nokomis Venice Inlet	8725899	0.534

Inundation elevations. The historical inundation data from an available NOAA gauge station in Fort Myers, FL (# 8725520) are shown in Figure 5 below. "HTU" is defined as a half-tide unit, or 50% of the great-diurnal tide range.

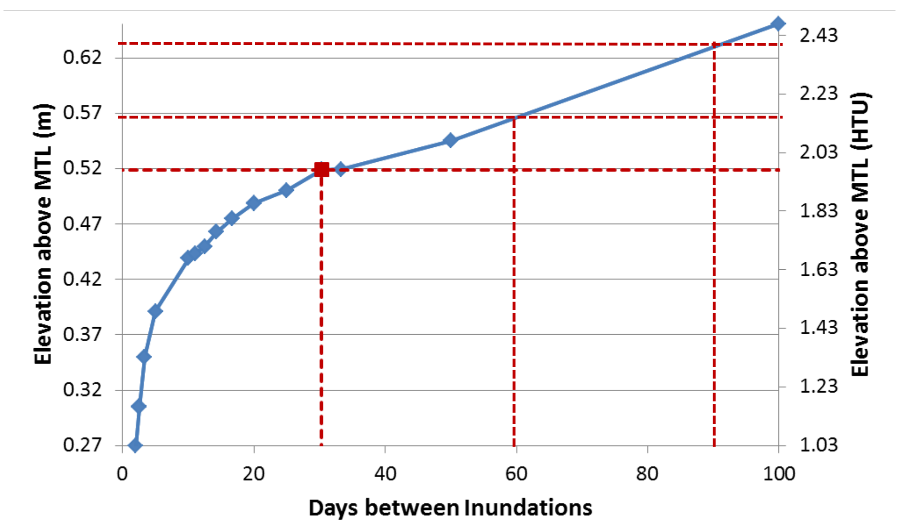


Figure 5. Inundation data at NOAA Gauge Station # 8725520 in Fort Myers, FL.

From these data, the inundation elevations for the study area are estimated as follows: elevations less than 1.97 HTU above MTL are inundated at least once every 30 days, elevations between 1.97 and 2.16 HTU above MTL are inundated once every 30 to 60 days, elevations between 2.16 and 2.4 HTU above MTL are inundated once every 60 to 90 days, while elevations greater than 2.4 HTU above MTL are inundated with a frequency that is less than once per 90 days. These inundation frequencies were applied to the study area on a subsite basis (Figure 6), correcting for differences in the tide range of each subsite.

Salt elevation. The "salt elevation" parameter within SLAMM designates the boundary between coastal wetlands and dry lands or fresh water wetlands. Within SLAMM modeling simulations this elevation is usually defined as the elevation over which flooding is predicted less than once in every 30 days. From the inundation analysis above, salt elevation is 1.97 HTU above MTL.

Accretion rates. No erosion, accretion or sedimentation values specific to this study area were found that would be suitable for use, therefore SLAMM default values were used.

Model Timesteps. Model forecast data is output for years 2025, 2050, 2075 and 2100 with the initial condition date set to 2008, the most recent wetland data available.

Erosion rates. Horizontal erosion of marshes and swamps occurs in SLAMM only at the wetland-to-open-water interface and only when adequate open water (fetch) exists for wave setup. Due to a lack of site-specific data, erosion rates were set to the SLAMM defaults of 2 horz. m/yr for marsh, 1 horz. m/yr for swamp and 0.5 horz. m/yr for tidal flat .

Elevation correction. The MTL to NAVD88 correction factors were obtained from nearby NOAA gauge stations and assigned on a subsite basis.

Refuge boundaries. Modeled USFWS refuge boundaries for Florida are based on Approved Acquisition Boundaries as published on the USFWS National Wildlife Refuge Data and Metadata website. The cell-size used for this analysis is 5 m.

Input subsites and parameter summary. Table 2 summarizes all SLAMM input parameters for the study area. Values for parameters with no specific local information were kept at the model default value.

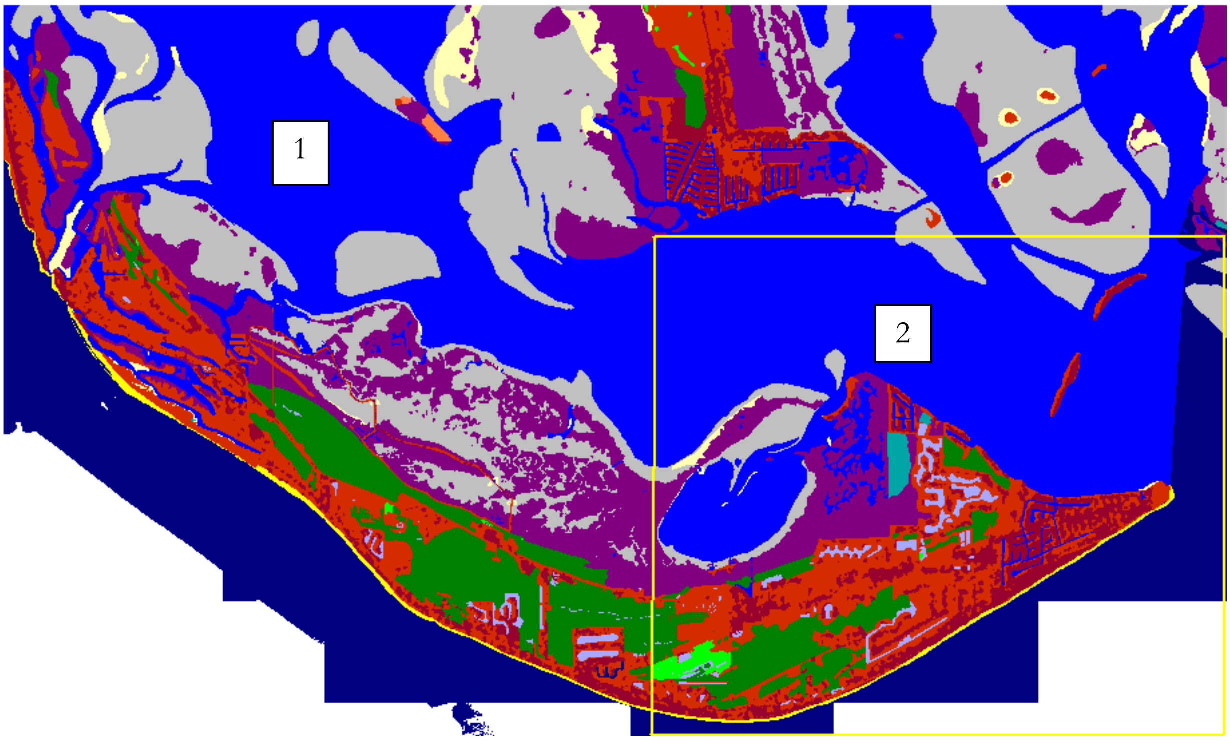


Figure 6. Input parameter subsites used

Table 2. Summary of SLAMM input parameters for J.N. "Ding" Darling NWR.

Parameter	SubSite 1	SubSite 2
Description	Charlotte Harbor	Estero
NWI Photo Date (YYYY)	2008	2008
DEM Date (YYYY)	2007	2007
Direction Offshore [n,s,e,w]	West	West
Historic Trend (mm/yr)	2.4	2.4
MTL-NAVD88 (m)	-0.178	-0.185
GT Great Diurnal Tide Range (m)	0.529	0.75
Salt Elev. (m above MTL)	0.52	0.74
Marsh Erosion (horz. m /yr)	2	2
Swamp Erosion (horz. m /yr)	1	1
T.Flat Erosion (horz. m /yr)	0.2	0.2
Reg.-Flood Marsh Accr (mm/yr)	2.25	2.25
Irreg.-Flood Marsh Accr (mm/yr)	3.75	3.75
Tidal-Fresh Marsh Accr (mm/yr)	4	4
Inland-Fresh Marsh Accr (mm/yr)	4	4
Mangrove Accr (mm/yr)	7	7
Tidal Swamp Accr (mm/yr)	1.1	1.1
Swamp Accretion (mm/yr)	0.3	0.3
Beach Sed. Rate (mm/yr)	0.3	0.3
Freq. Overwash (years)	0	0
Use Elev Pre-processor [True,False]	FALSE	FALSE
30-D Inundation (m above MTL)	0.52	0.74
60-D Inundation (m above MTL)	0.57	0.81
90-D Inundation (m above MTL)	0.63	0.9
Storm Surge Test (m above MTL)	1	1

Model Initial Conditions

Initially, SLAMM simulates a "time zero" step, in which the consistency of model assumptions for wetland elevations is validated with respect to available wetland coverage information, elevation data and tidal frames. Due to simplifications within the SLAMM conceptual model, DEM and wetland layer uncertainty, or other local factors, some cells may fall below their lowest allowable elevation category and would be immediately converted by the model to a different land cover category (e.g. an area categorized in the wetland layer as swamp where water has a tidal regime according to its elevation and tidal information will be converted to a tidal marsh). These cells represent outliers on the distribution of elevations for a given land-cover type. Generally, a threshold tolerance of up to 5% change is allowed for in major wetland land cover categories in SLAMM analyses.

For this refuge, "time zero" wetland coverage is very consistent with the provided wetland layer with only minor changes predicted in covered areas as shown in Table 3. These results support initial validation of the model and consistency with available data and tidal information.

Table 3. Comparison of refuge initial land cover from the wetland layer and initial coverage predicted by the SLAMM model

Land cover type		Areas (acres)	
		NWI 2008	**SLAMM 2008**
	Mangrove	3101	3193
	Tidal Flat	1699	1699
	Swamp	1329	1310
	Estuarine Open Water	950	952
	Undeveloped Dry Land	742	670
	Inland Fresh Marsh	84	85
	Estuarine Beach	59	59
	Developed Dry Land	56	53
	Inland Open Water	35	34
	Open Ocean	6	23
	Ocean Beach	29	13
	Regularly Flooded Marsh	6	6
	Inland Shore	5	5
	Tidal Swamp	1	1
	Total (incl. water)	**8103**	**8103**

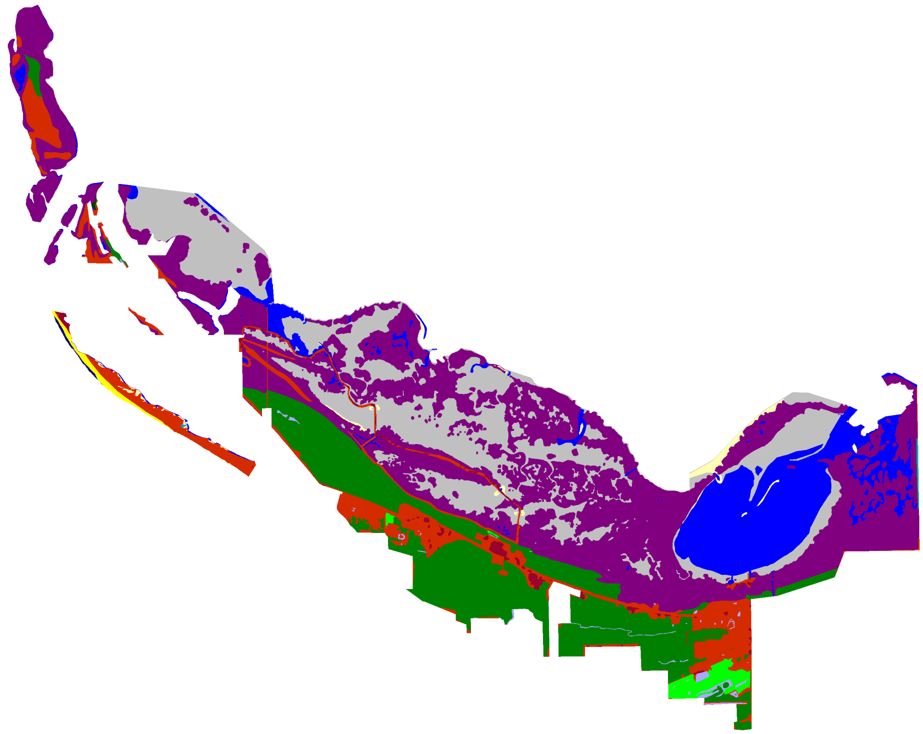


Figure 7. Initial 2008 NWI wetland layer

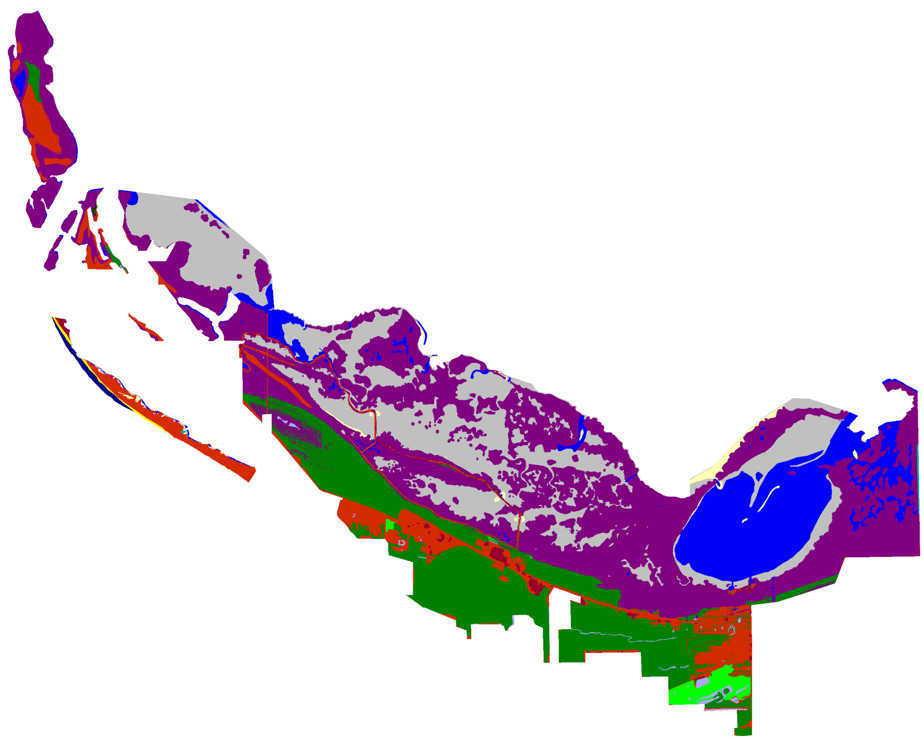


Figure 8. 2008 SLAMM “time zero” result

Results

Wetland coverage projections

SLAMM simulations suggest J.N. 'Ding' Darling NWR will be somewhat impacted by all the SLR scenarios examined. As shown in Table 4, severe impacts are noted in scenarios of 0.69 m of SLR by 2100 and greater. Accounting for the effects of road systems on inundation pathways did not significantly change model results, with the exception of inland marsh as is discussed below.

Mangrove makes up the majority of the refuge. This habitat type is predicted to increase by 2100 for SLR scenarios 1 m by 2100 and lower. The highest amount of expansion is observed in the 0.69 m scenario, when the SLR simulated is nearly equal to the mangrove accretion rate applied (7 mm/yr). However, when SLR outpaces the mangrove accretion rate, extreme losses of mangrove are predicted, culminating in maximum loss of 94% at 2 m SLR by 2100.

Tidal flat and swamp are the second and third most prominent land cover types in the refuge, respectively. Major losses of these categories are predicted starting at 0.69 m of SLR by 2100 and above, with mangrove migrating into the areas previously inhabited by these land cover types as shown by the maps in the following section.

A small region of inland-fresh marsh exists in the refuge. Compared to previous predictions, this wetland category appears to be protected by the roads that act as protective dikes. Therefore predictions show a slightly higher resiliency with respect to the lowest SLR scenario considered. However, for SLR higher than 0.39 m by 2100 inundations of this marsh become more frequent and complete loss is predicted for scenarios of 1.5 m SLR by 2100 and above.

Table 4. Predicted loss rates of land categories by 2100 given simulated scenarios of eustatic SLR at J.N. "Ding" Darling NWR.

Land cover category	Initial coverage (acres)	Land cover loss by 2100 for different SLR scenarios				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Mangrove	3101	-26%	-45%	-41%	67%	94%
Tidal Flat	1699	1%	98%	100%	100%	100%
Swamp	1329	39%	70%	87%	95%	97%
Undeveloped Dry Land	742	38%	59%	76%	93%	98%
Beach (ocean and estuarine)	88	12%	48%	33%	40%	57%
Inland Fresh Marsh	84	24%	71%	91%	99%	100%

Losses of wetland habitats of one type may be balanced with gains in other habitat categories. However, for this refuge most predicted wetland losses are due to permanent inundation by the increasing sea level. Approximately 34% of the refuge is predicted to be permanently under water under by 2100 under 0.69 m SLR scenario, from the current 12% coverage. For higher SLR scenarios more refuge area is predicted to be permanently inundated, culminating with open water covering 97% of the refuge area by 2100 under 2 m SLR scenario. Gains of open water coverage are summarized in Table 5.

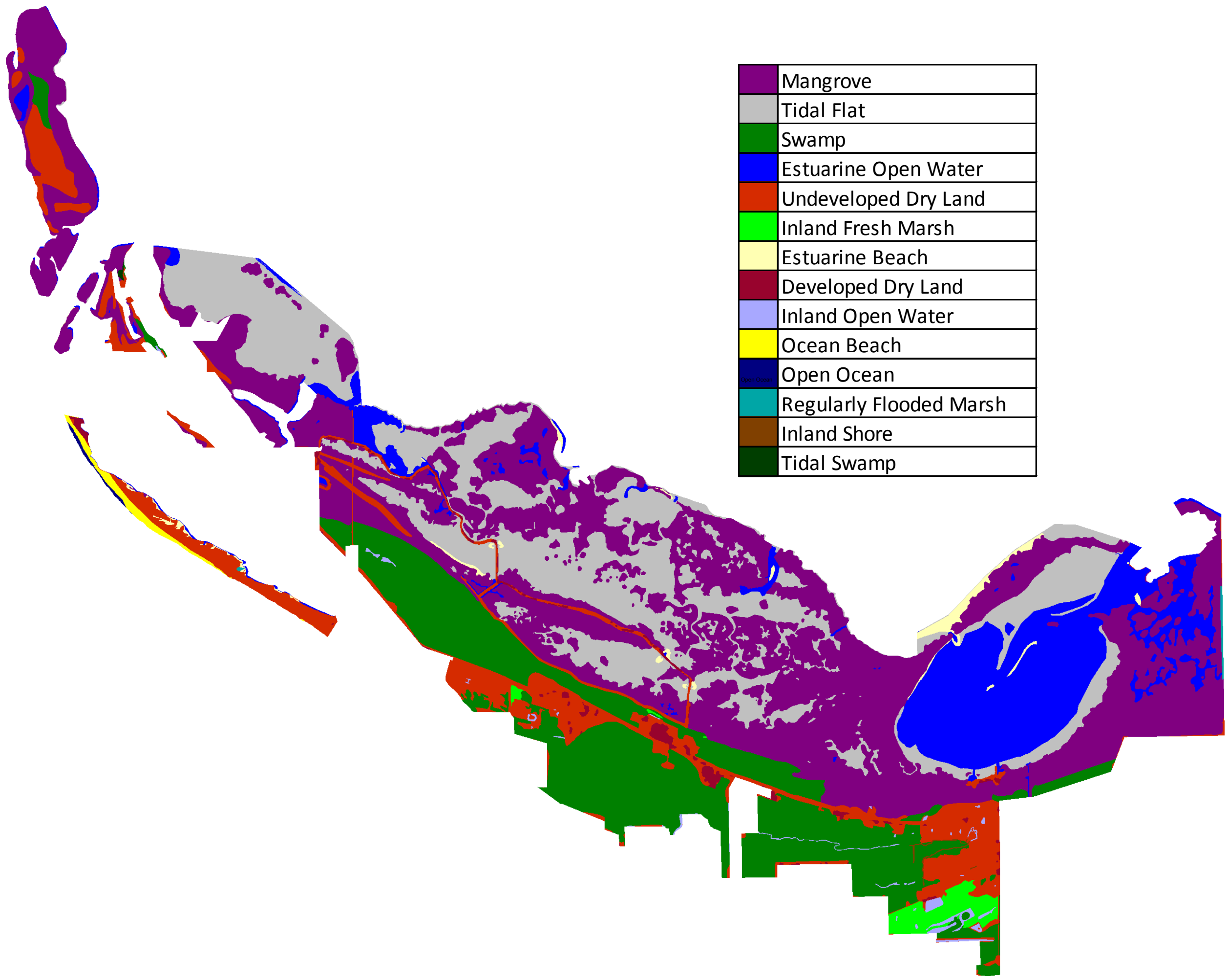
Table 5. Predicted land cover gains by 2100 given simulated scenarios of eustatic SLR at J.N. "Ding" Darling NWR.

Land cover category	Initial coverage (acres)	Land cover by 2100 for different SLR scenarios (acres)				
		0.39 m	0.69 m	1 m	1.5 m	2 m
Open water	991	1048	2753	3266	6897	7820

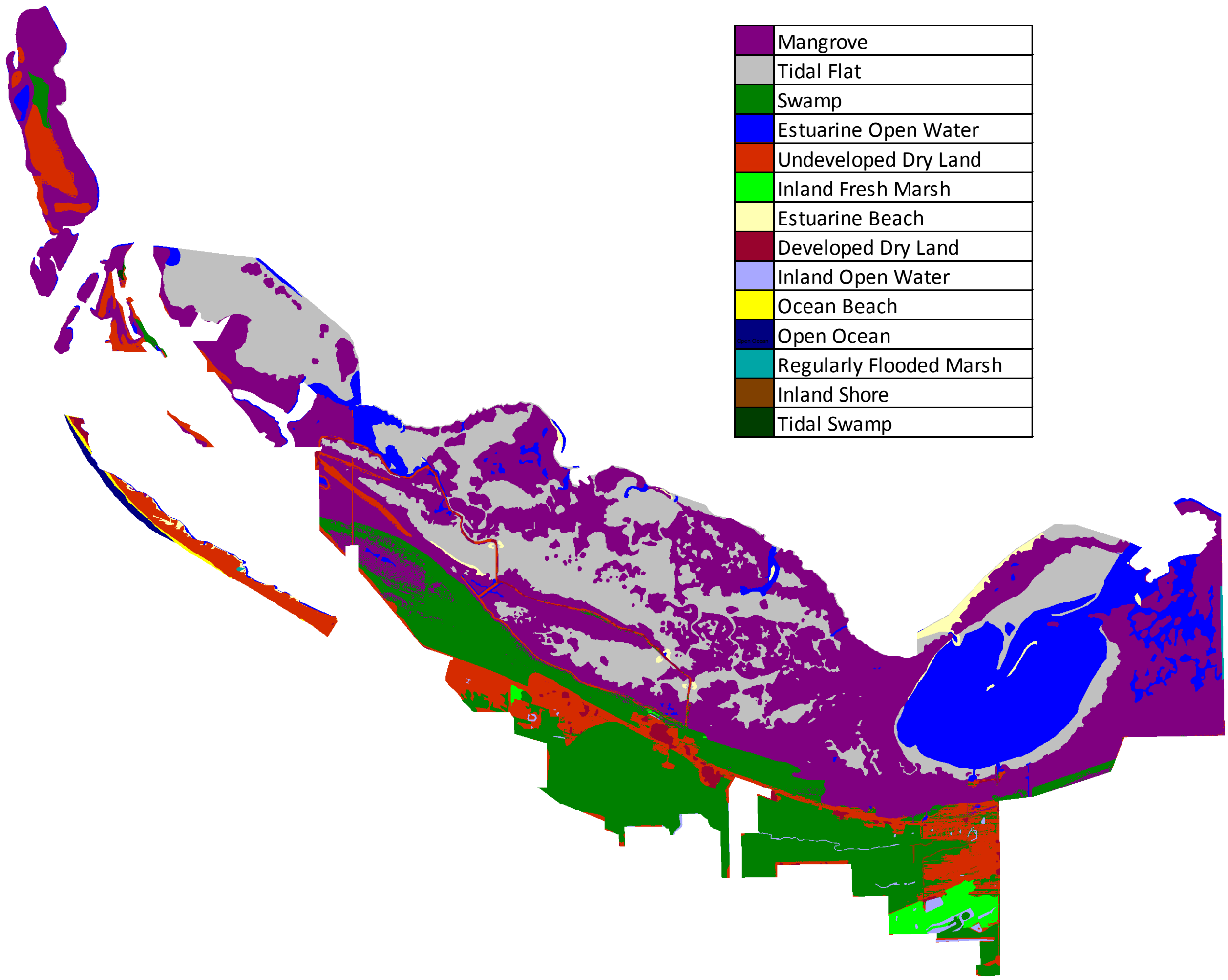
J.N. "Ding" Darling NWR
IPCC Scenario A1B-Mean, 0.39 m SLR eustatic by 2100

Results in Acres

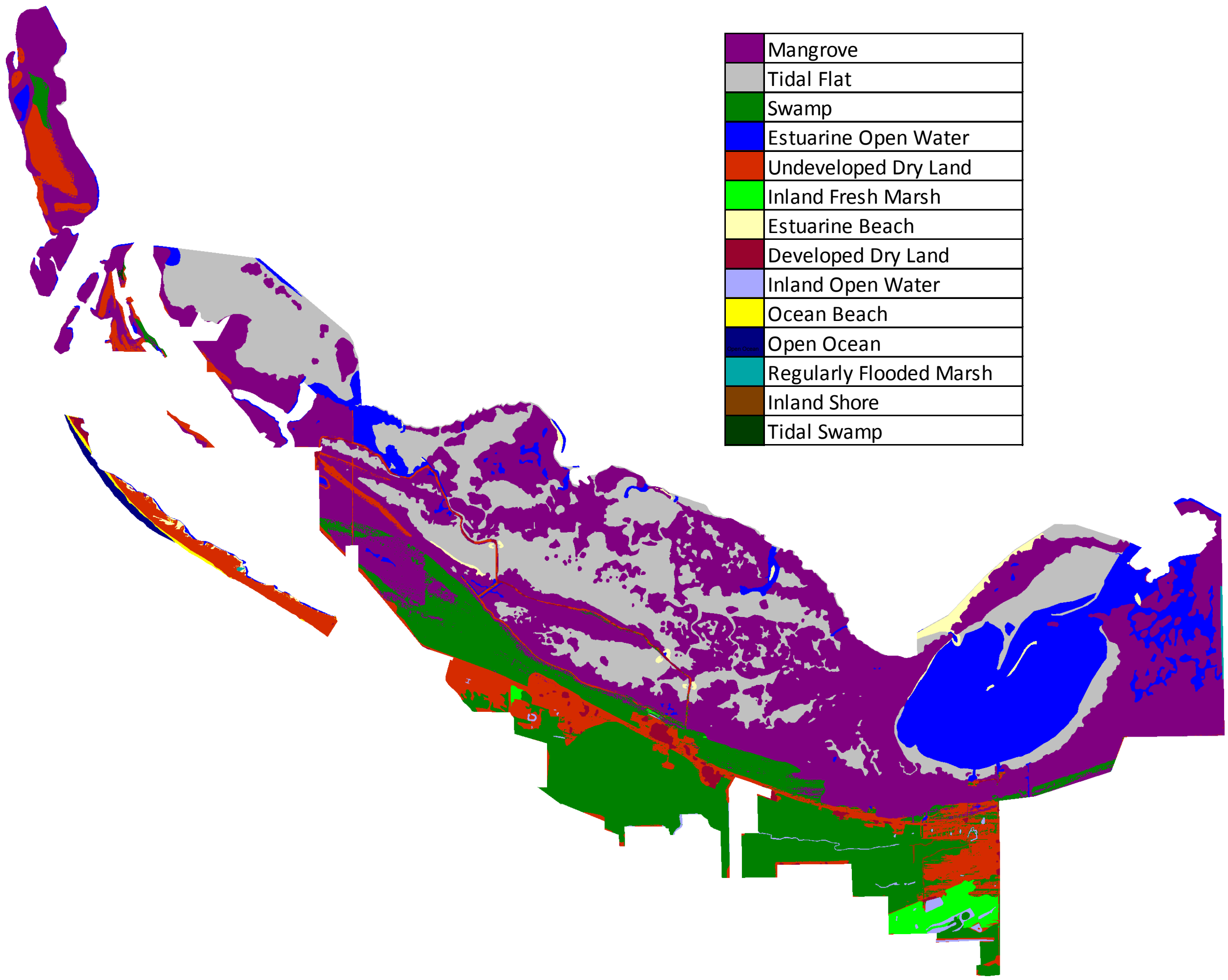
		Initial	2025	2050	2075	2100
	Mangrove	3101	3309	3425	3645	3914
	Tidal Flat	1699	1694	1692	1686	1676
	Swamp	1329	1242	1164	1006	809
	Estuarine Open Water	950	988	991	998	1017
	Undeveloped Dry Land	742	635	598	536	458
	Inland Fresh Marsh	84	68	68	66	64
	Estuarine Beach	59	59	60	61	63
	Developed Dry Land	56	51	50	49	46
	Inland Open Water	35	8	8	7	3
	Open Ocean	6	24	25	26	28
	Ocean Beach	29	12	12	12	14
	Regularly Flooded Marsh	6	6	6	6	6
	Inland Shore	5	5	5	4	4
	Tidal Swamp	1	1	1	1	0
	Total (incl. water)	**8103**	**8103**	**8103**	**8103**	**8103**



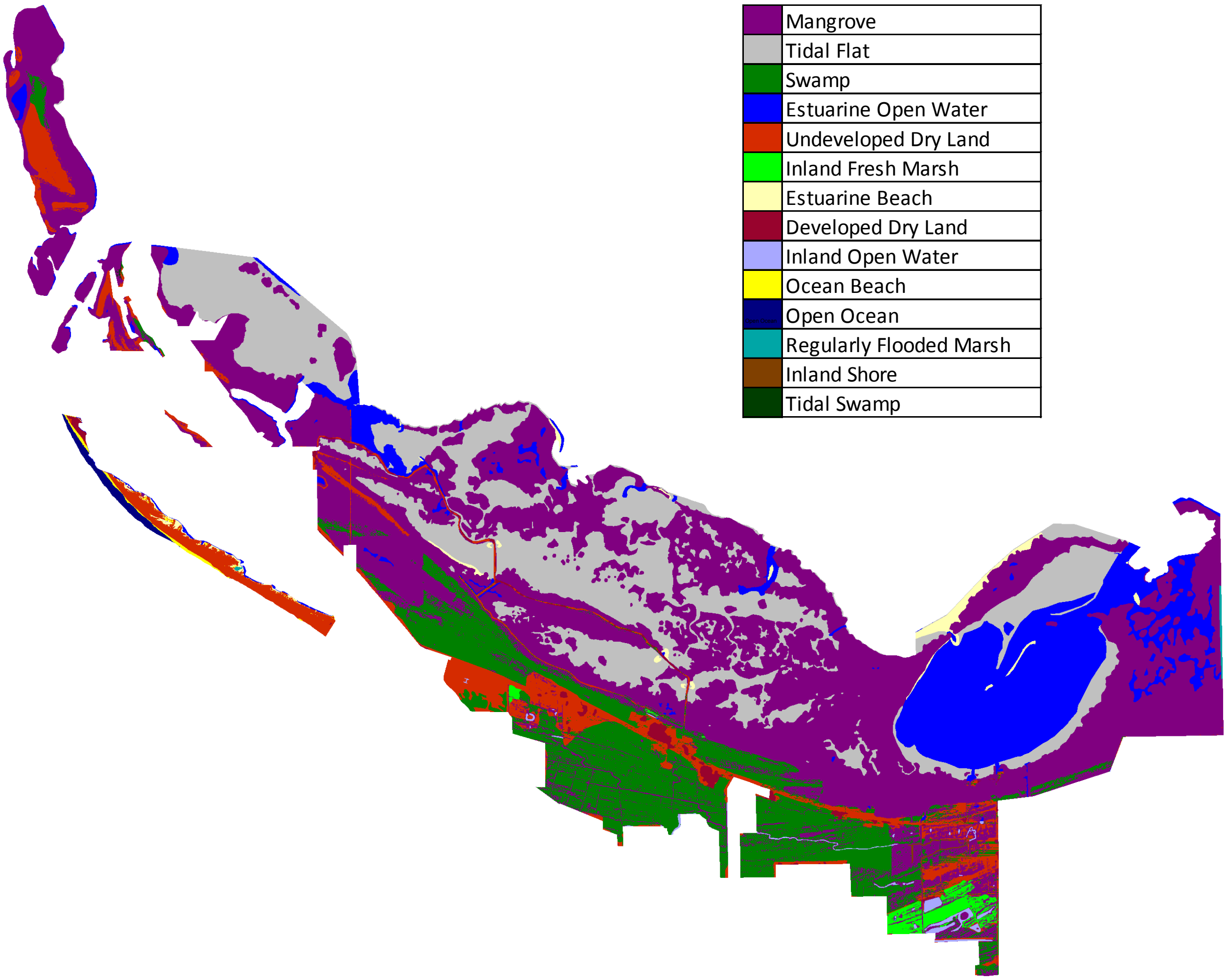
J.N. "Ding" Darling NWR, Initial Conditions.



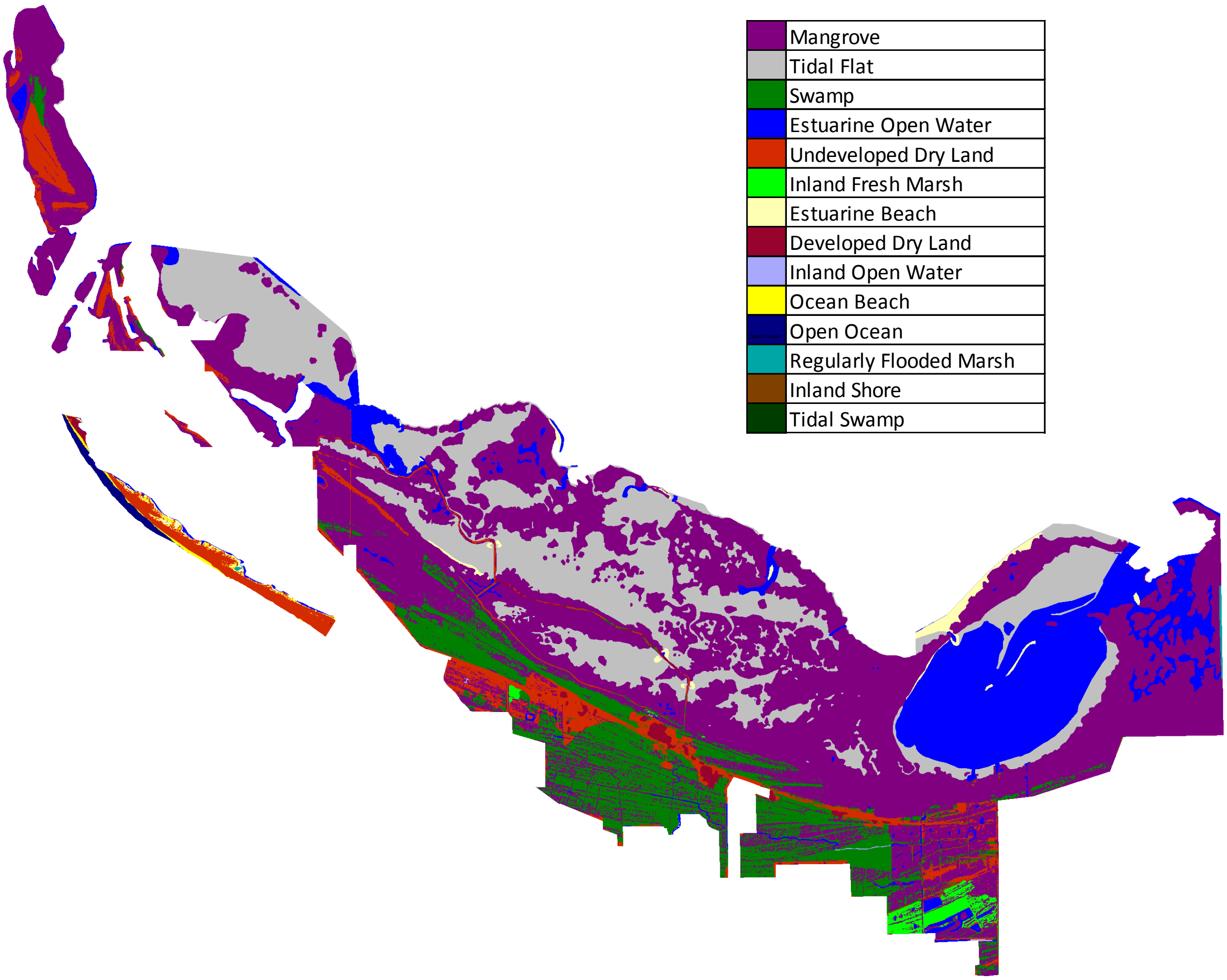
J.N. "Ding" Darling NWR, 2025, Scenario A1B Mean, 0.39 m SLR



J.N. "Ding" Darling NWR, 2050, Scenario A1B Mean, 0.39 m SLR by 2100.



J.N. "Ding" Darling NWR, 2075, Scenario A1B Mean, 0.39 m SLR by 2100.

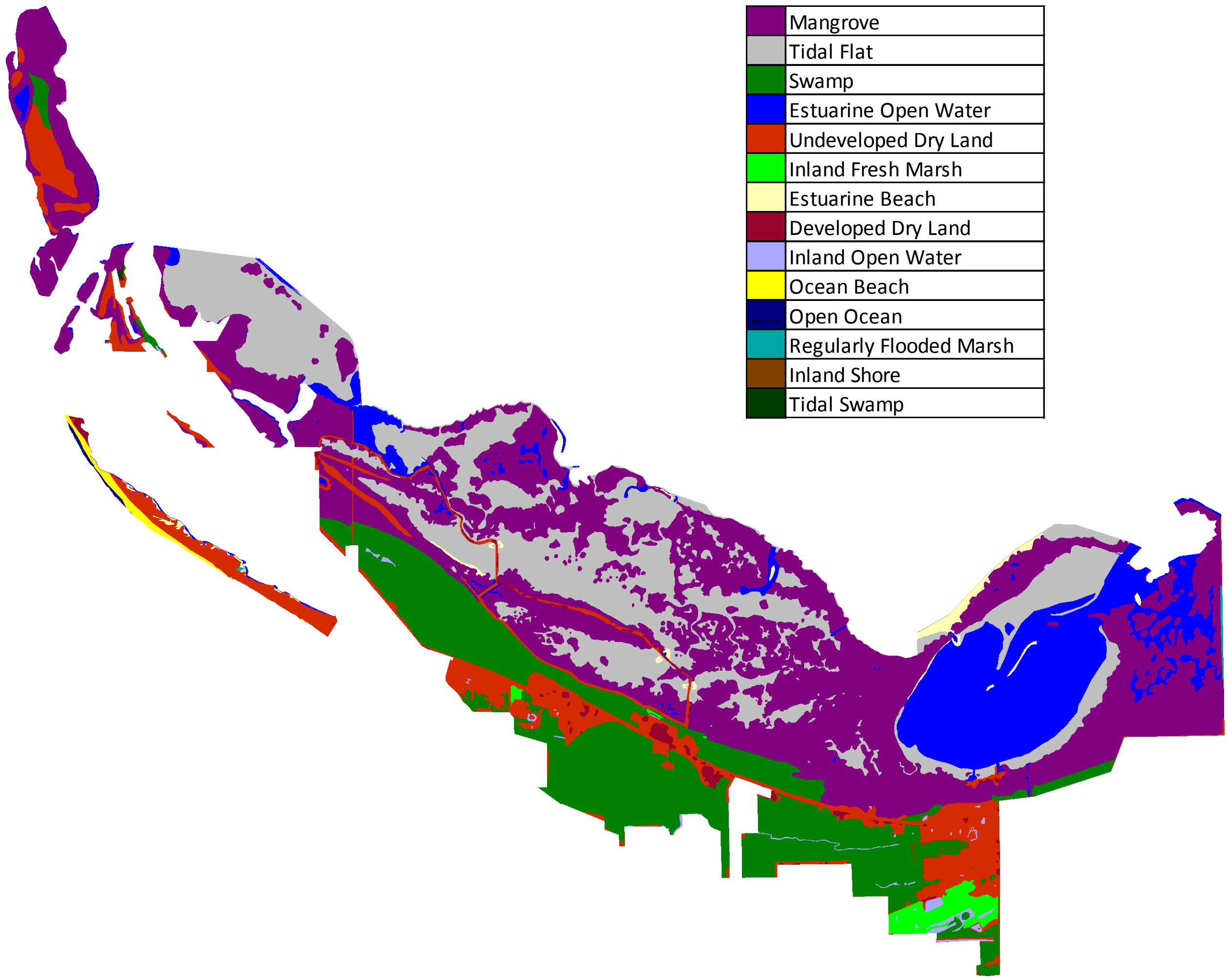


J.N. "Ding" Darling NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.

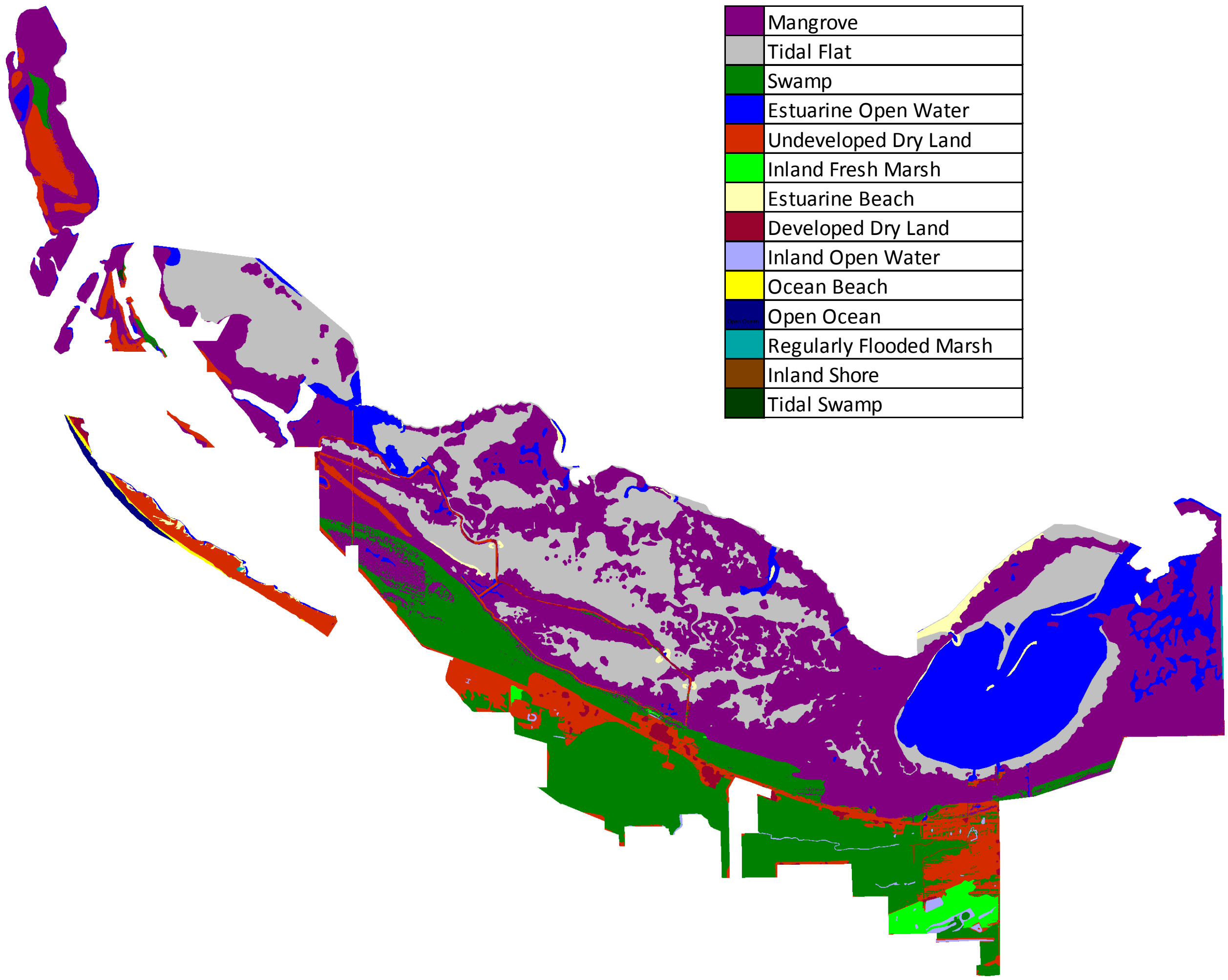
J.N. "Ding" Darling NWR
IPCC Scenario A1B-Max, 0.69 m SLR eustatic by 2100

Results in Acres

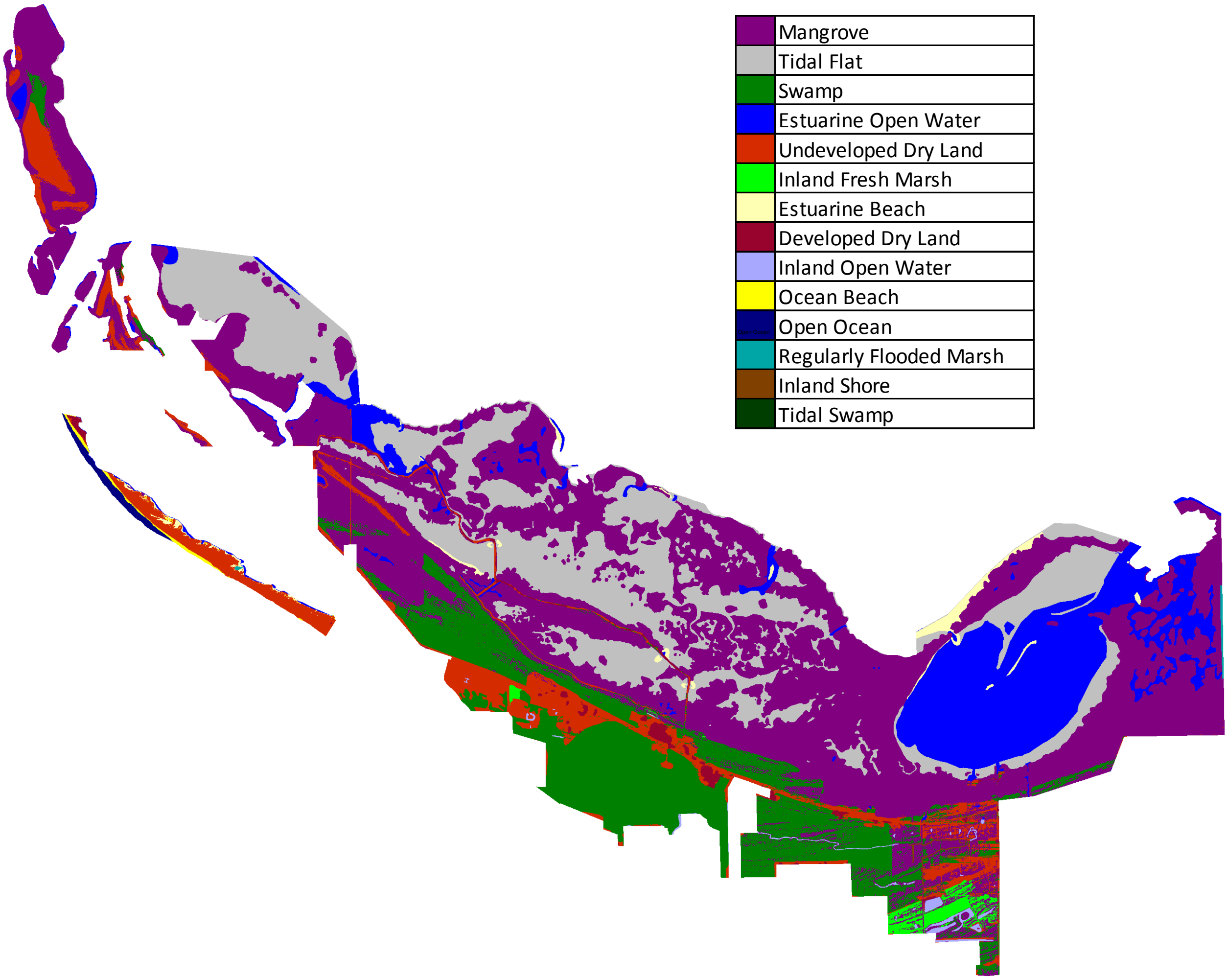
		Initial	2025	2050	2075	2100
	Mangrove	3101	3334	3595	4069	4488
	Tidal Flat	1699	1694	1692	386	40
	Swamp	1329	1225	1042	698	398
	Estuarine Open Water	950	988	992	2325	2723
	Undeveloped Dry Land	742	628	556	431	307
	Inland Fresh Marsh	84	67	60	40	25
	Estuarine Beach	59	59	61	54	22
	Developed Dry Land	56	51	49	45	40
	Inland Open Water	35	8	7	3	2
	Open Ocean	6	24	25	27	28
	Ocean Beach	29	12	12	15	24
	Regularly Flooded Marsh	6	6	6	6	4
	Inland Shore	5	5	4	4	2
	Tidal Swamp	1	1	1	0	0
	Total (incl. water)	**8103**	**8103**	**8103**	**8103**	**8103**



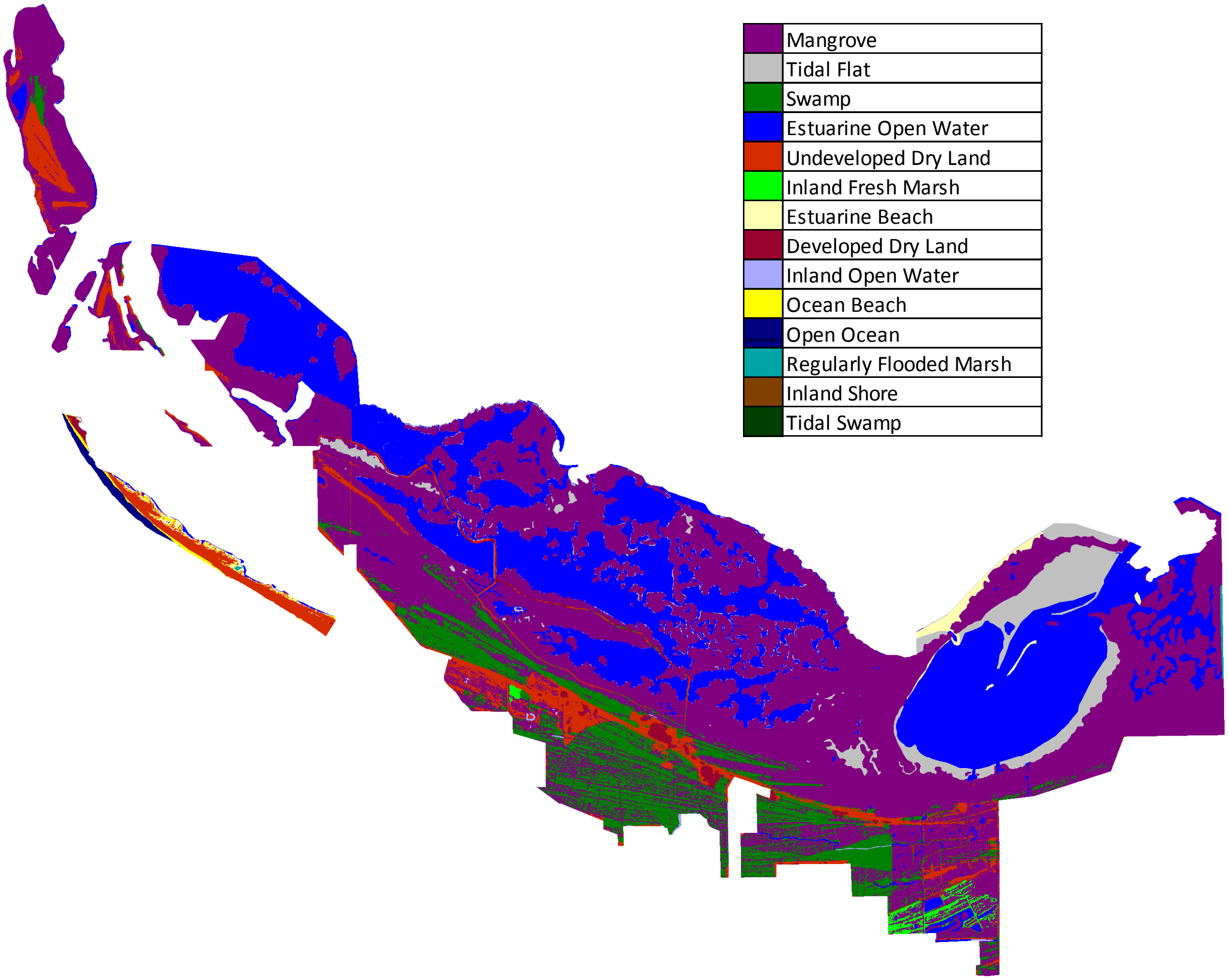
J.N. "Ding" Darling NWR, Initial Conditions.



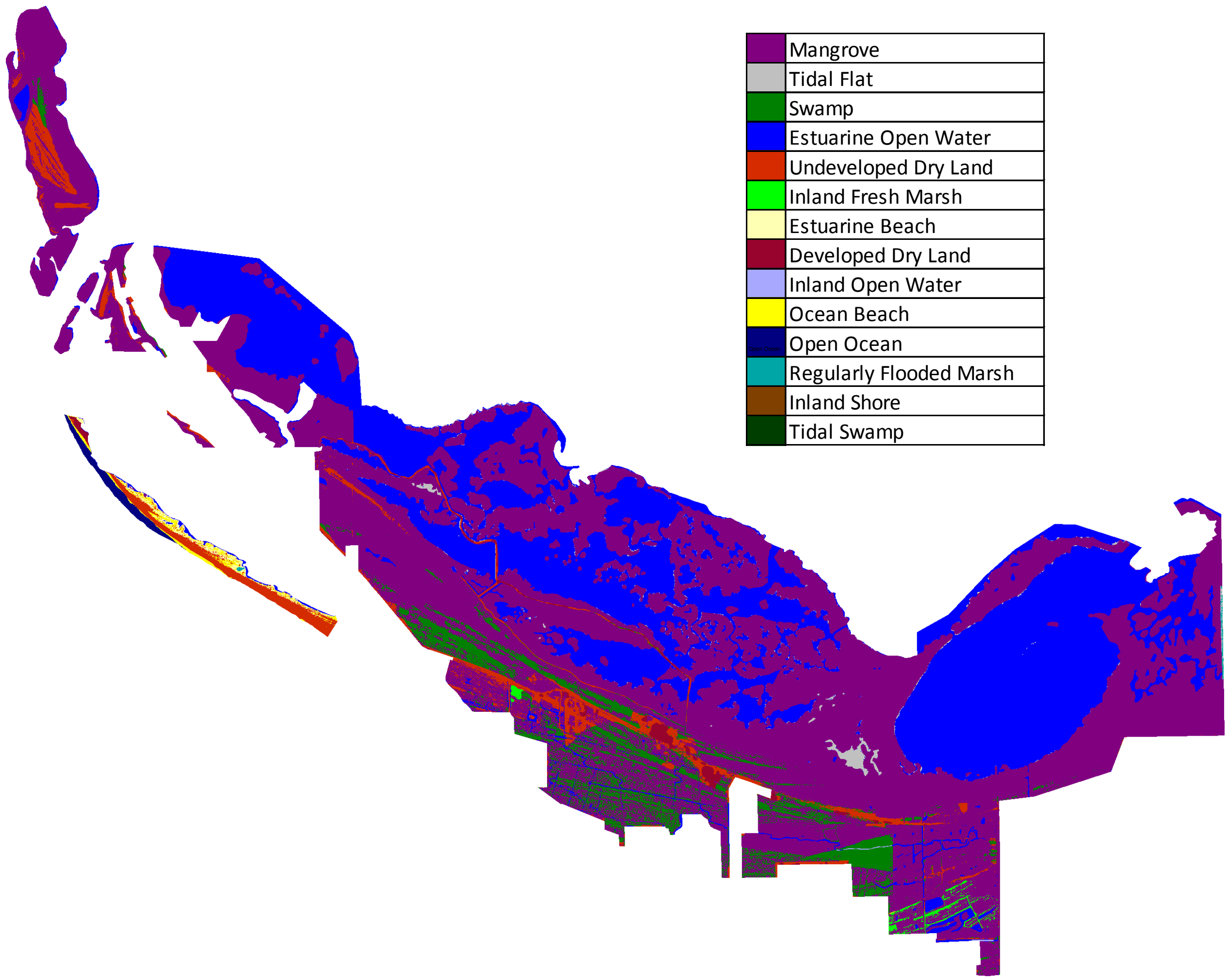
J.N. “Ding” Darling NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



J.N. "Ding" Darling NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



J.N. “Ding” Darling NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.

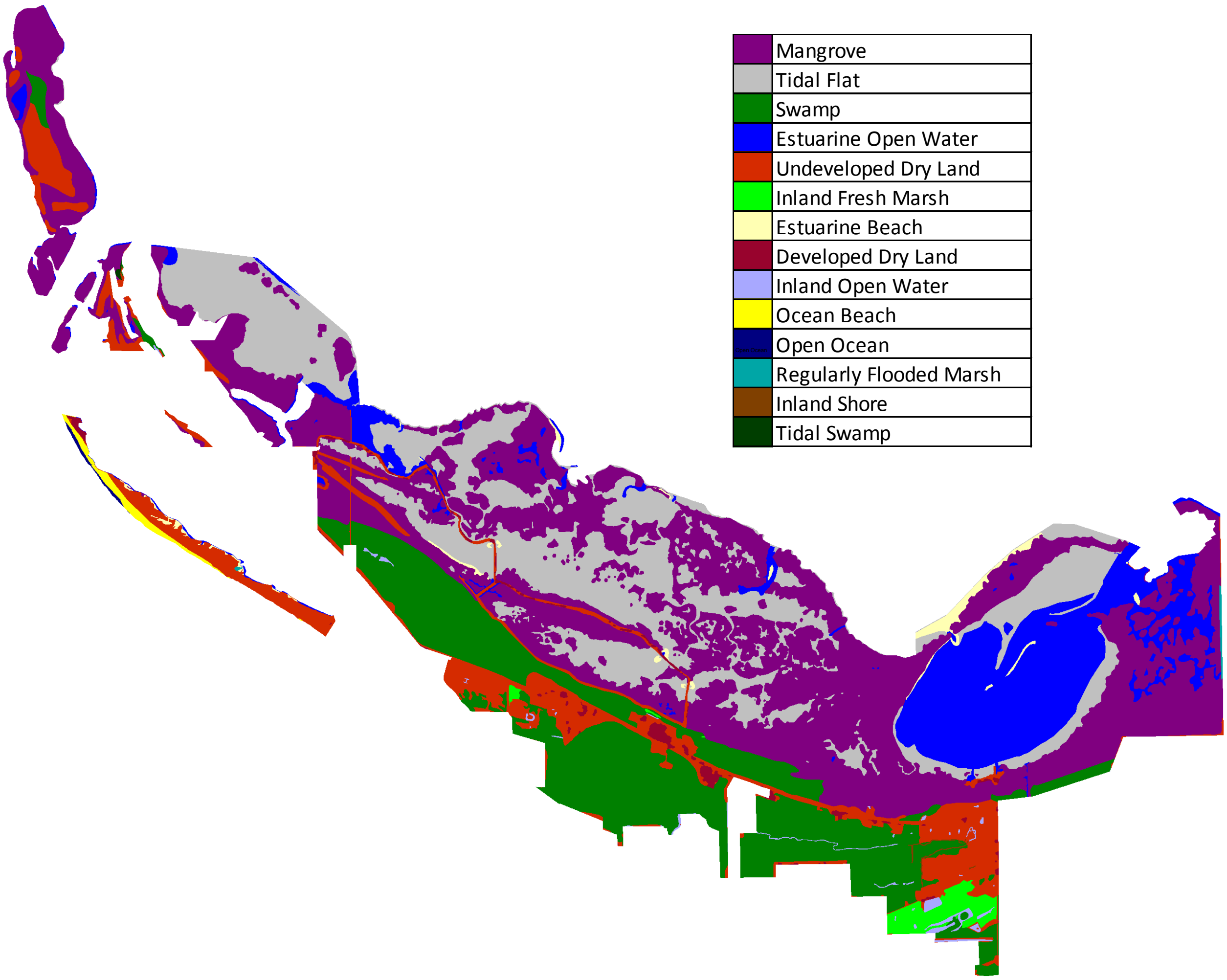


J.N. “Ding” Darling NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.

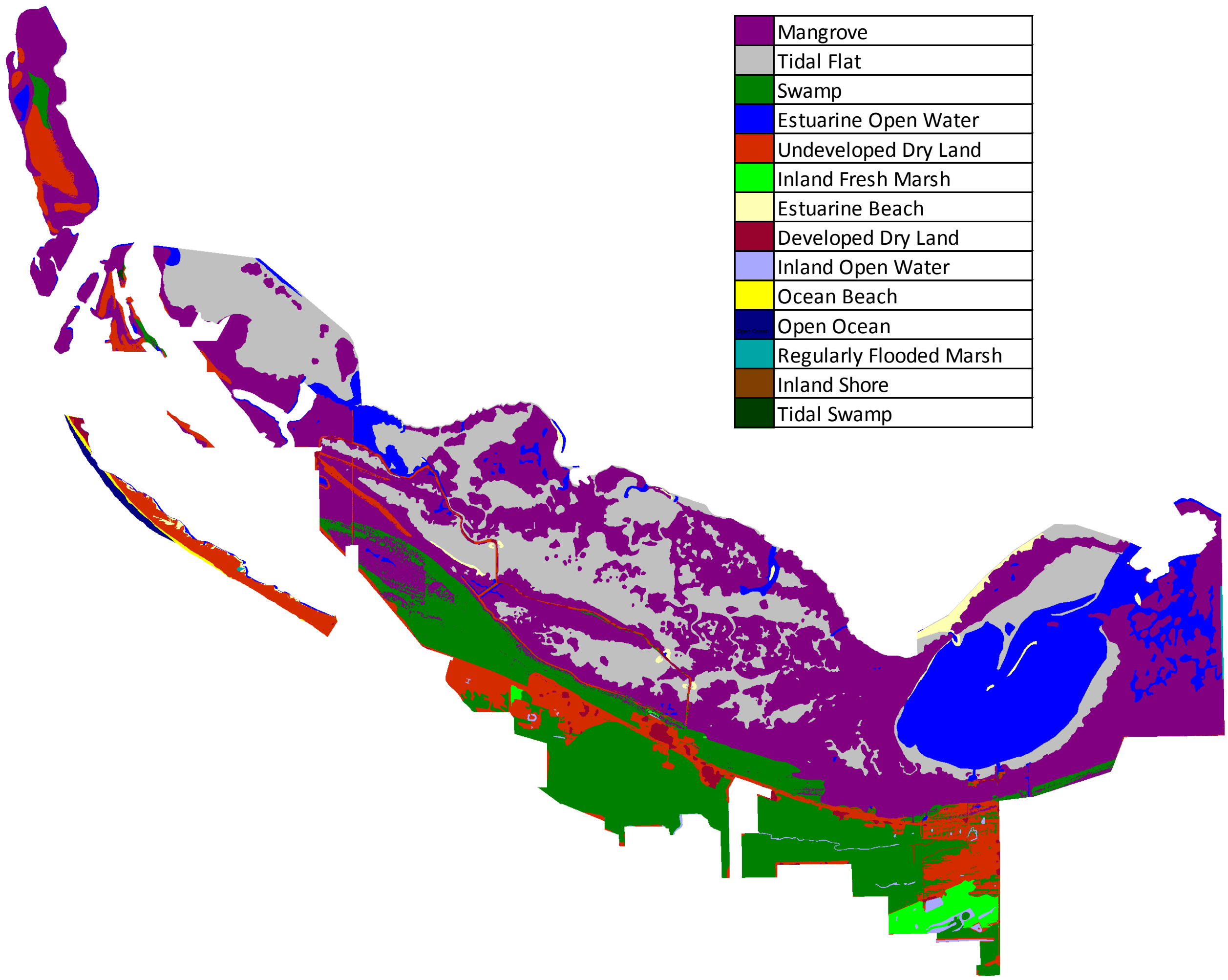
J.N. "Ding" Darling NWR
1 m eustatic SLR by 2100

Results in Acres

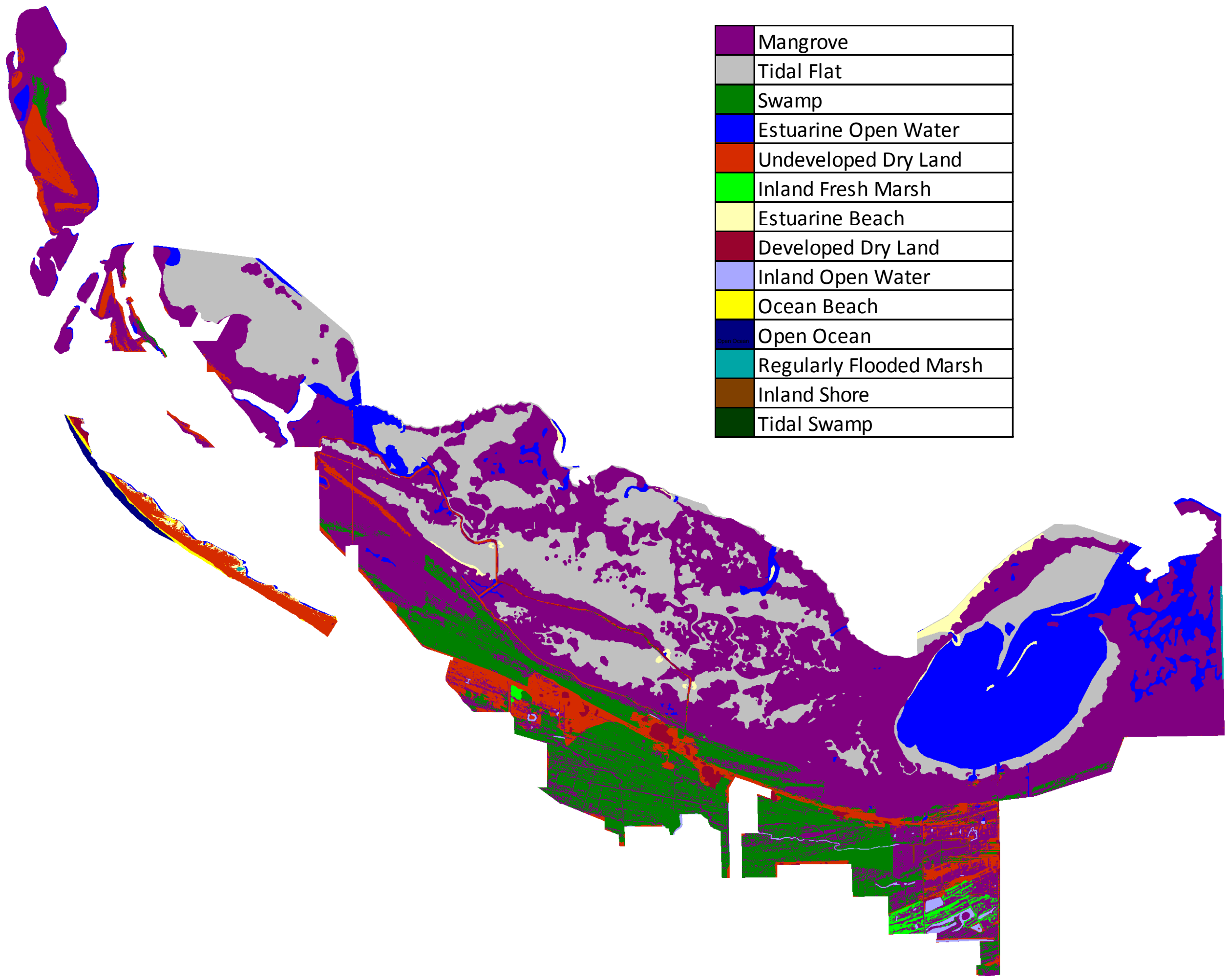
		Initial	2025	2050	2075	2100
	Mangrove	3101	3365	3805	4327	4381
	Tidal Flat	1699	1694	1692	48	8
	Swamp	1329	1203	896	436	176
	Estuarine Open Water	950	989	997	2822	3234
	Undeveloped Dry Land	742	620	503	330	177
	Inland Fresh Marsh	84	65	43	20	8
	Estuarine Beach	59	59	64	24	23
	Developed Dry Land	56	51	48	41	27
	Inland Open Water	35	8	7	2	2
	Open Ocean	6	24	25	27	30
	Ocean Beach	29	12	13	21	36
	Regularly Flooded Marsh	6	6	6	3	0
	Inland Shore	5	5	4	2	1
	Tidal Swamp	1	1	0	0	0
	Total (incl. water)	**8103**	**8103**	**8103**	**8103**	**8103**



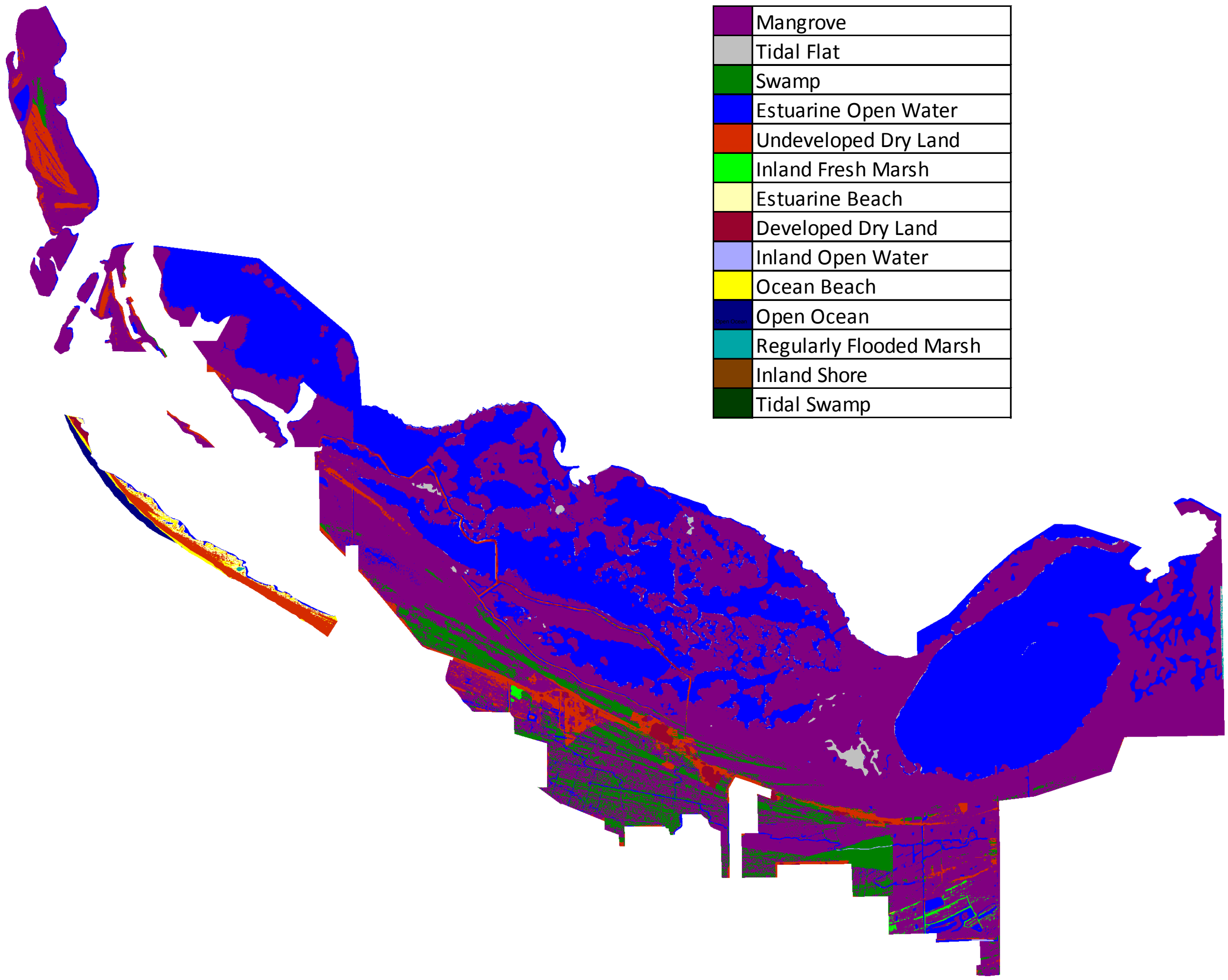
J.N. “Ding” Darling NWR, Initial Conditions.



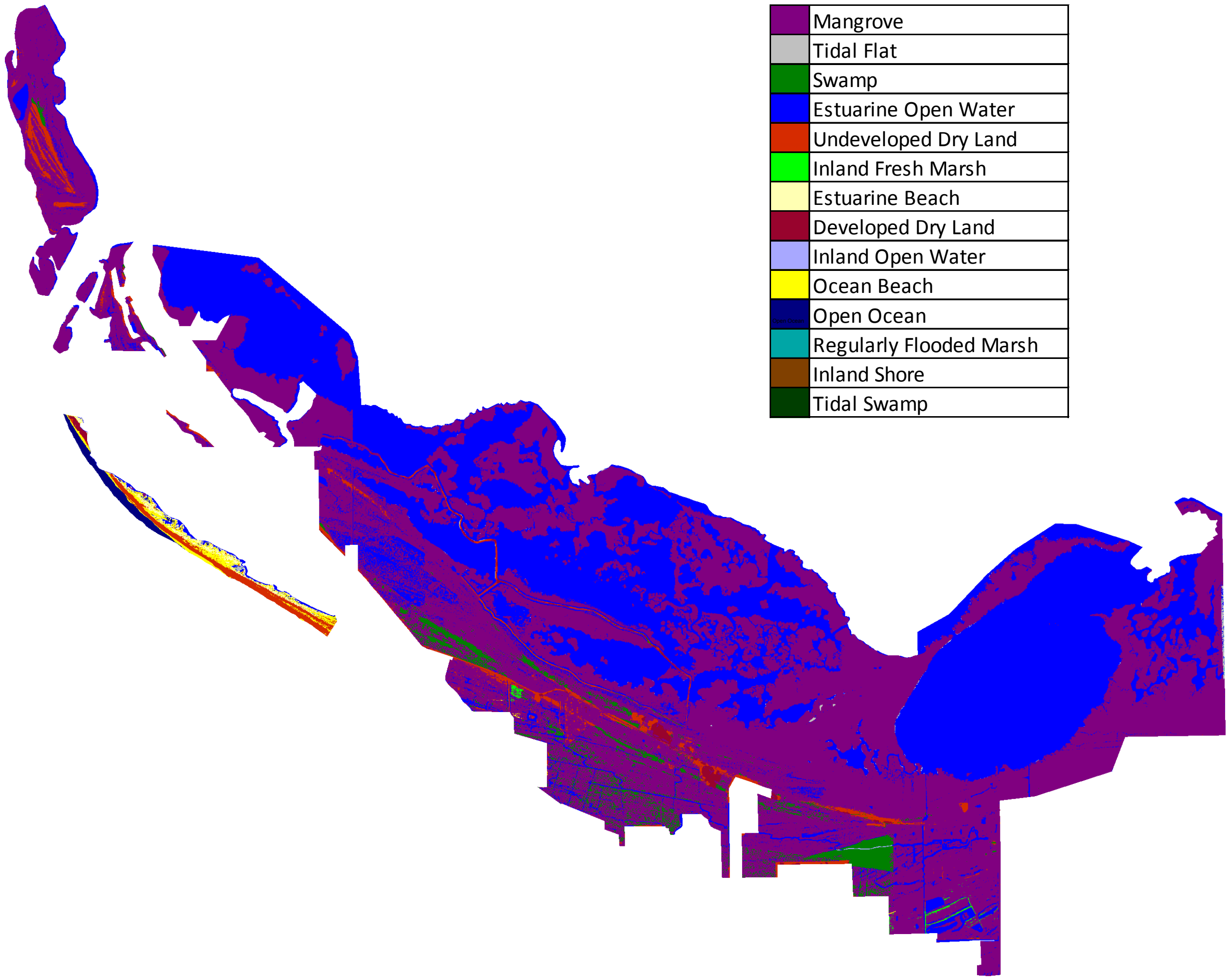
J.N. "Ding" Darling NWR, 2025, 1 m SLR by 2100.



J.N. "Ding" Darling NWR, 2050, 1 m SLR by 2100.



J.N. “Ding” Darling NWR, 2075, 1 m SLR by 2100.

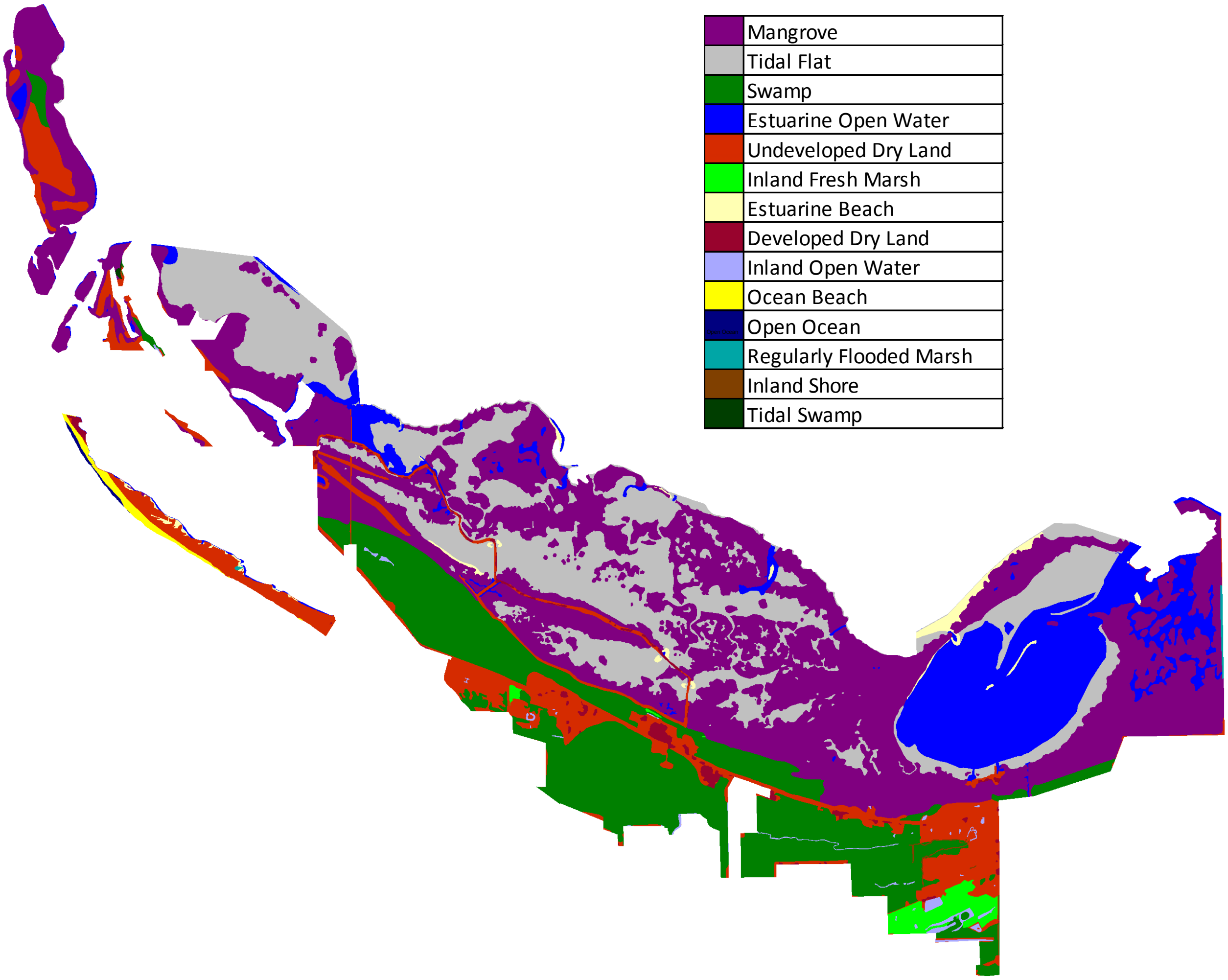


J.N. "Ding" Darling NWR, 2100, 1 m SLR by 2100.

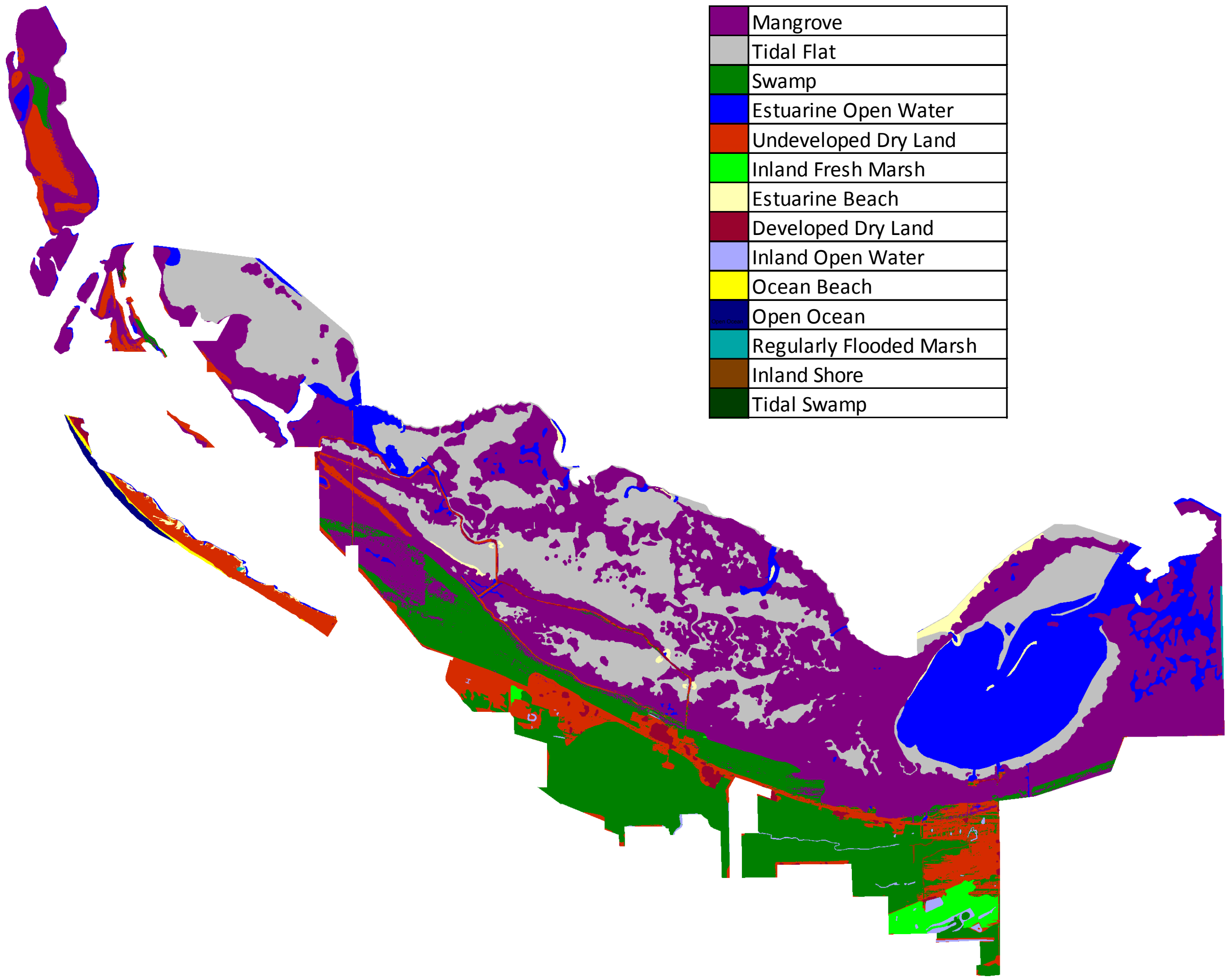
J.N. "Ding" Darling NWR
1.5 m eustatic SLR by 2100

Results in Acres

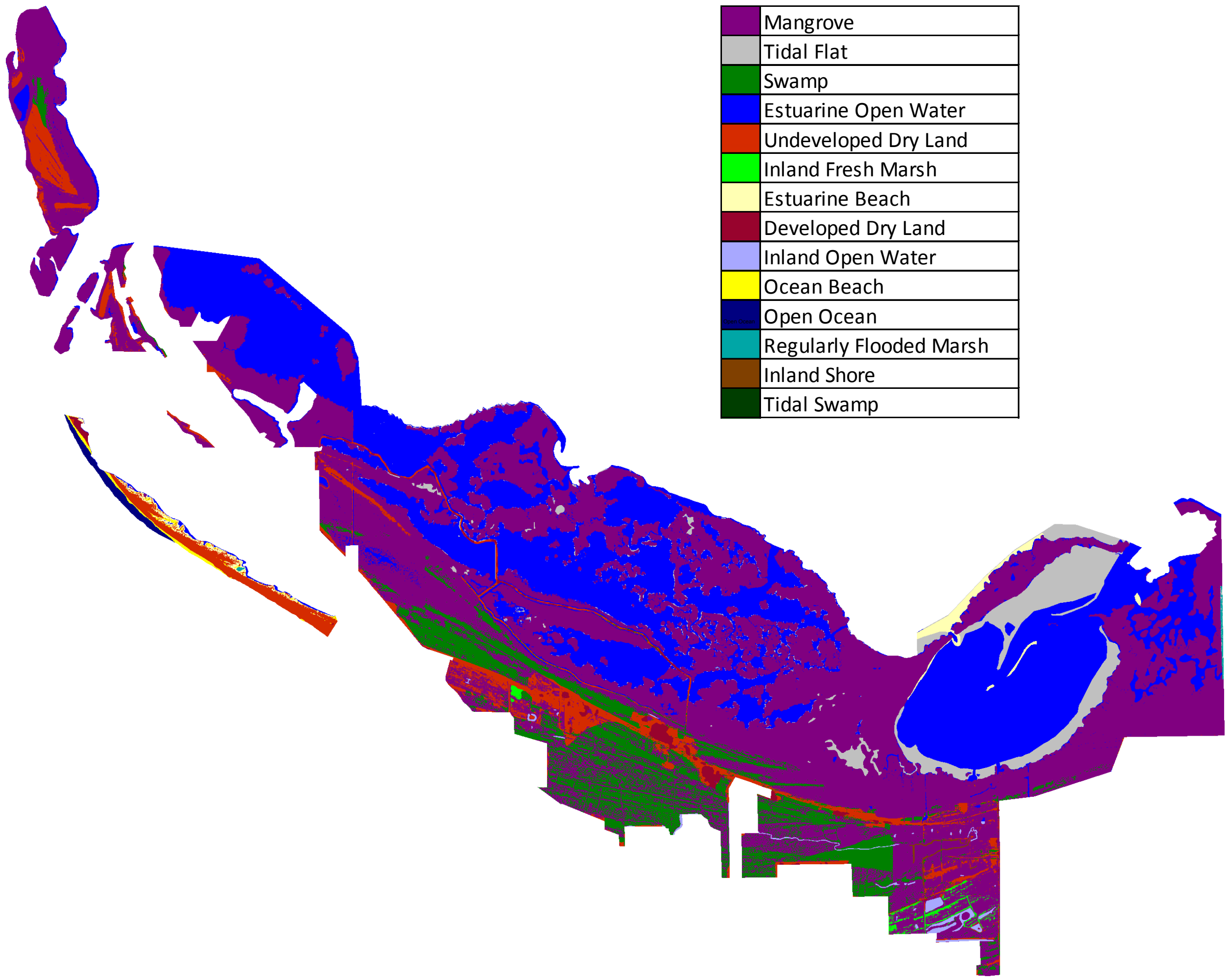
		Initial	2025	2050	2075	2100
	Mangrove	3101	3423	4023	3638	1028
	Tidal Flat	1699	1694	334	9	1
	Swamp	1329	1163	624	181	62
	Estuarine Open Water	950	991	2528	3965	6851
	Undeveloped Dry Land	742	605	414	186	51
	Inland Fresh Marsh	84	60	24	6	1
	Estuarine Beach	59	60	56	26	12
	Developed Dry Land	56	50	45	28	10
	Inland Open Water	35	8	7	2	2
	Open Ocean	6	24	26	29	44
	Ocean Beach	29	12	15	33	42
	Regularly Flooded Marsh	6	6	5	0	0
	Inland Shore	5	5	3	1	0
	Tidal Swamp	1	1	0	0	0
	Total (incl. water)	**8103**	**8103**	**8103**	**8103**	**8103**



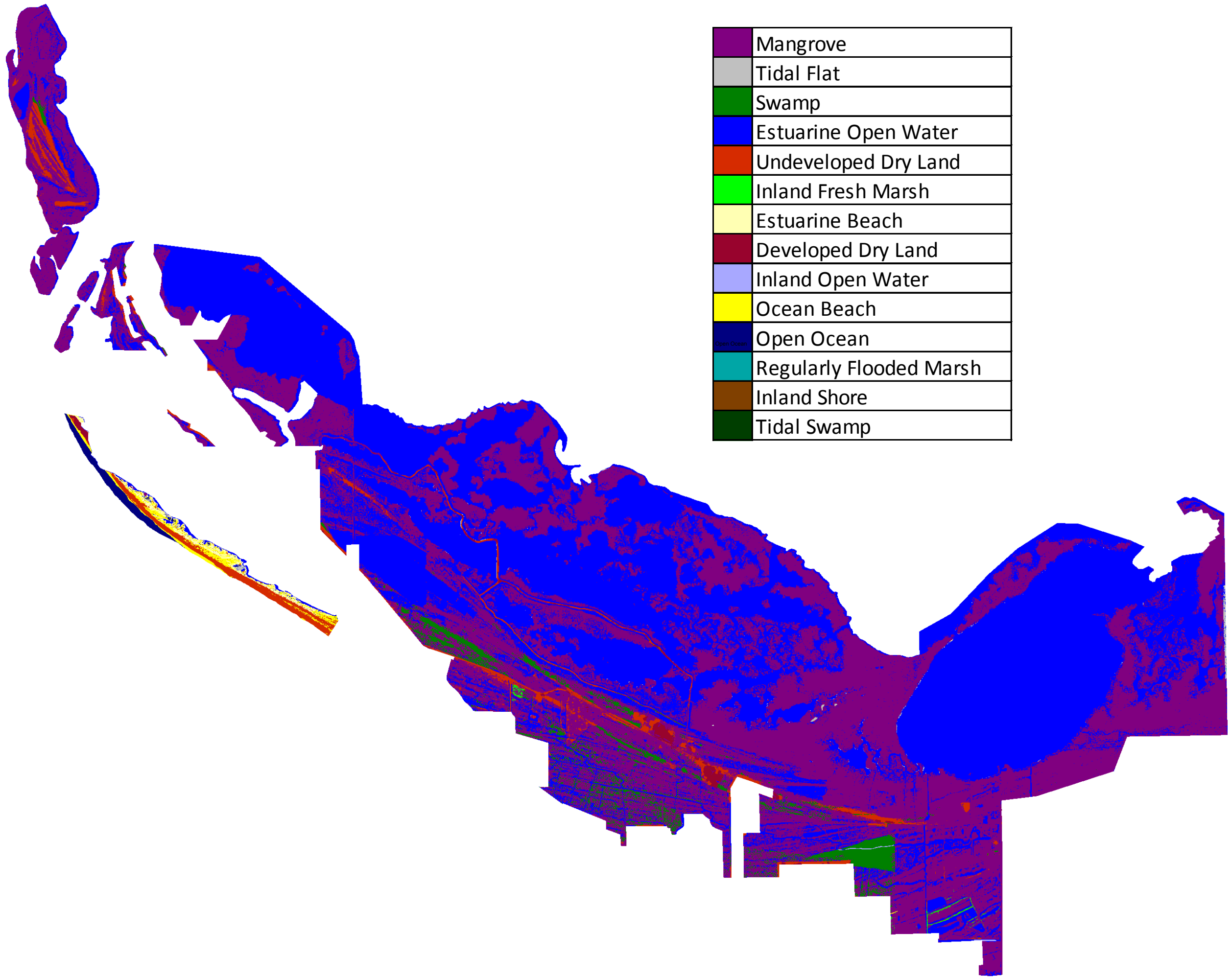
J.N. “Ding” Darling NWR, Initial Conditions.



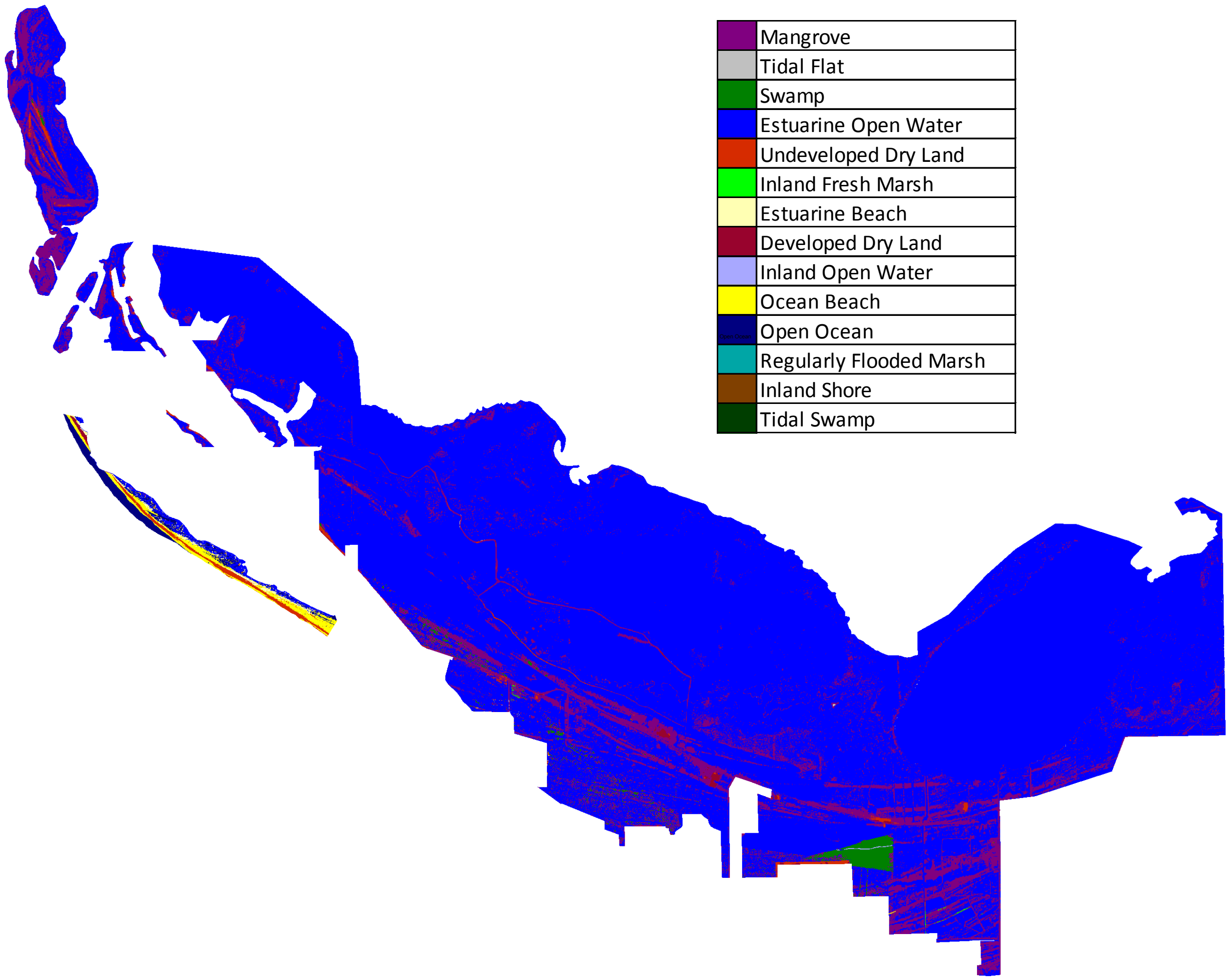
J.N. “Ding” Darling NWR, 2025, 1.5 m SLR by 2100.



J.N. “Ding” Darling NWR, 2050, 1.5 m SLR by 2100.



J.N. “Ding” Darling NWR, 2075, 1.5 m SLR by 2100.

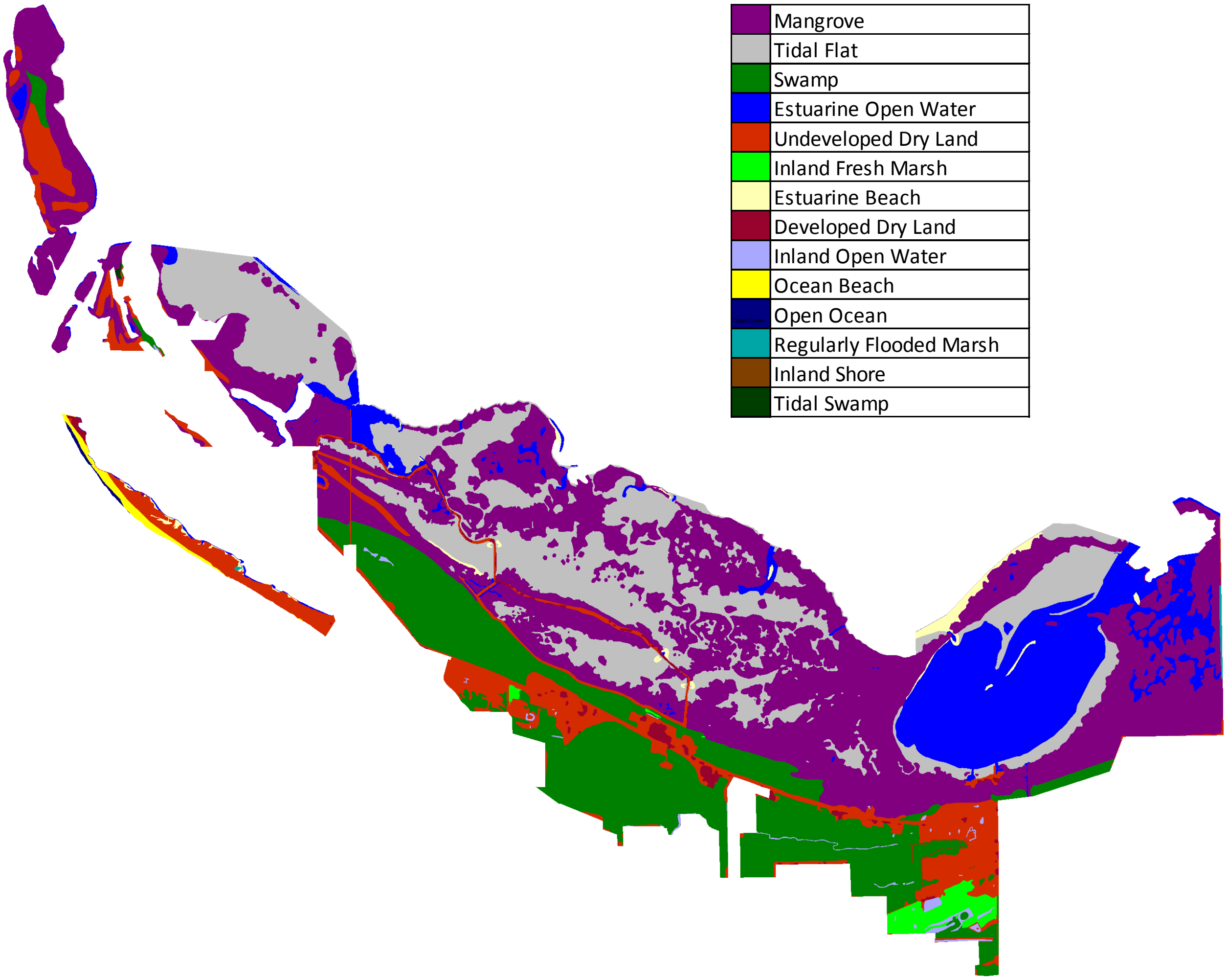


J.N. “Ding” Darling NWR, 2100, 1.5 m SLR by 2100.

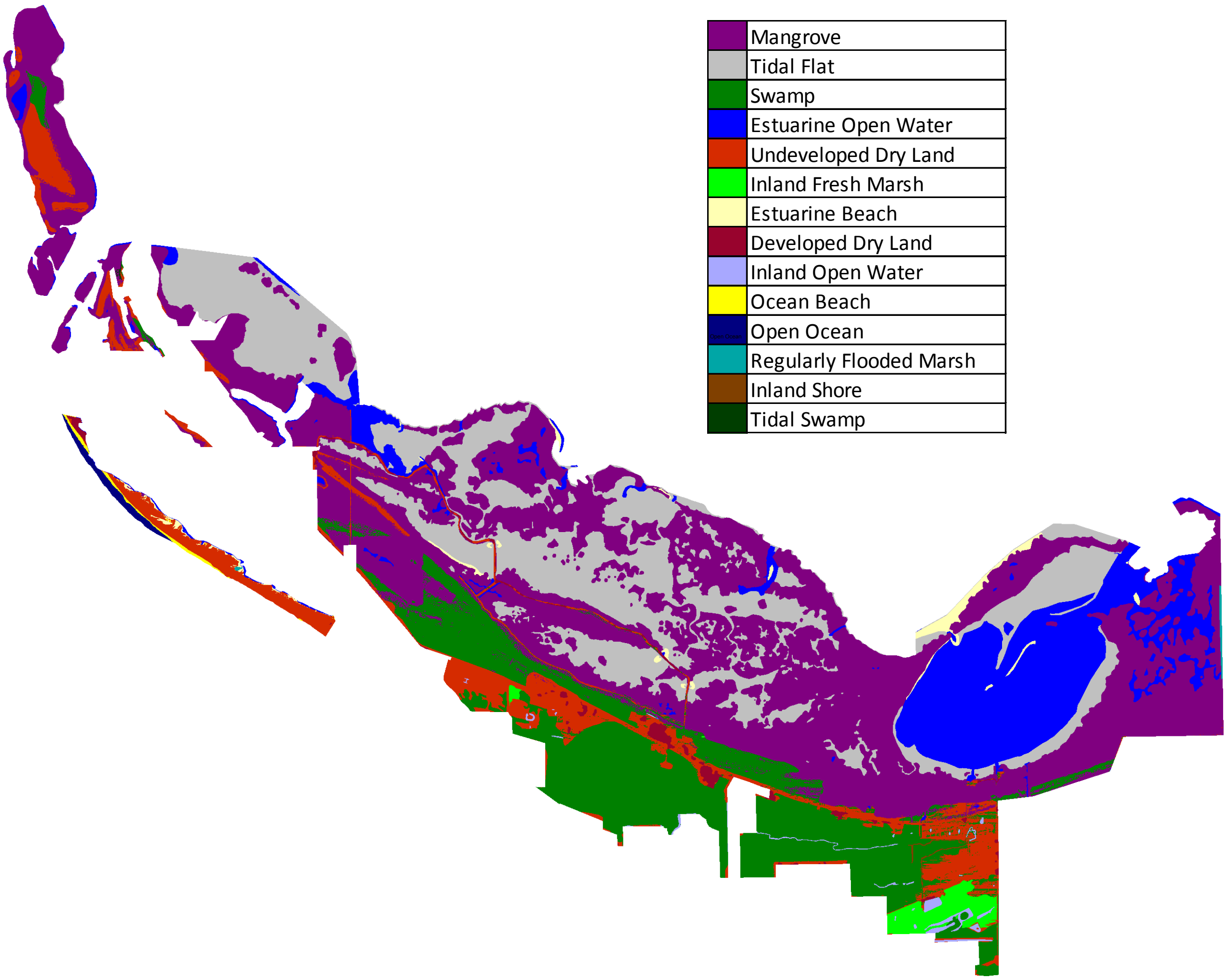
J.N. "Ding" Darling NWR
2 m eustatic SLR by 2100

Results in Acres

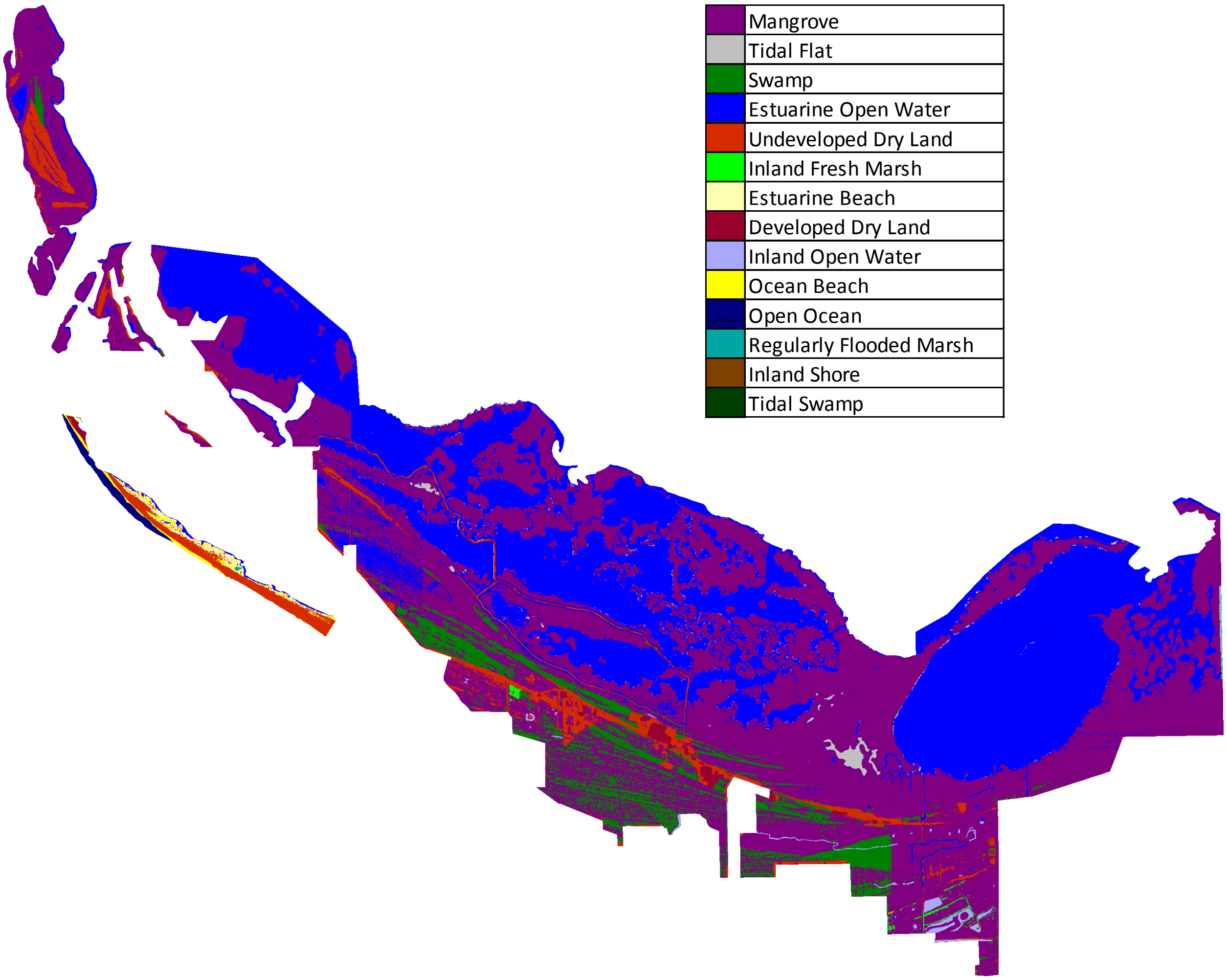
		Initial	2025	2050	2075	2100
	Mangrove	3101	3479	4050	1176	187
	Tidal Flat	1699	1694	44	3	0
	Swamp	1329	1125	415	83	42
	Estuarine Open Water	950	995	3128	6649	7750
	Undeveloped Dry Land	742	589	330	81	11
	Inland Fresh Marsh	84	56	13	2	0
	Estuarine Beach	59	60	28	16	5
	Developed Dry Land	56	50	41	15	4
	Inland Open Water	35	8	7	2	2
	Open Ocean	6	24	26	34	69
	Ocean Beach	29	12	18	41	33
	Regularly Flooded Marsh	6	6	2	0	0
	Inland Shore	5	5	2	0	0
	Tidal Swamp	1	1	0	0	0
	Total (incl. water)	**8103**	**8103**	**8103**	**8103**	**8103**



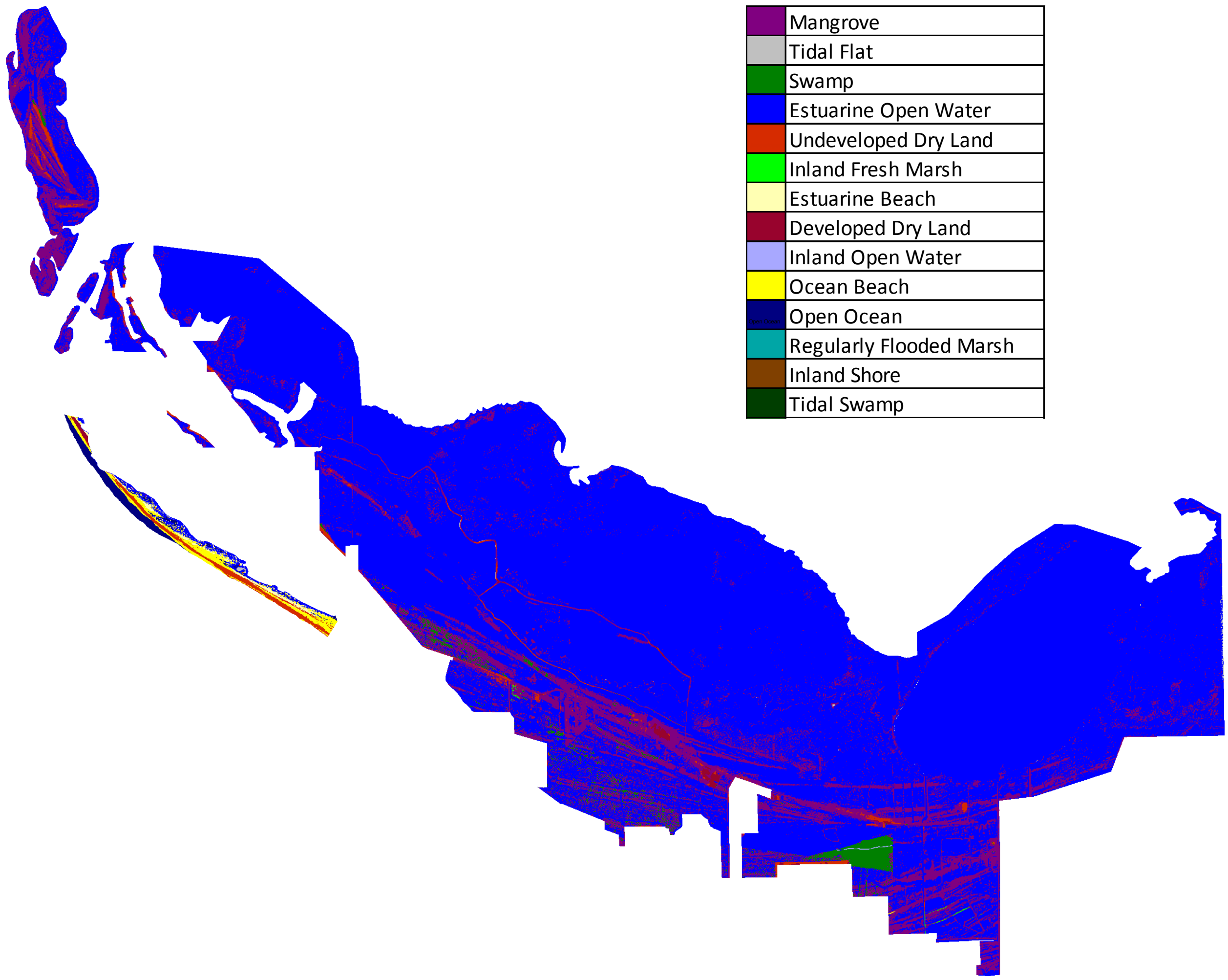
J.N. "Ding" Darling NWR, Initial Conditions.



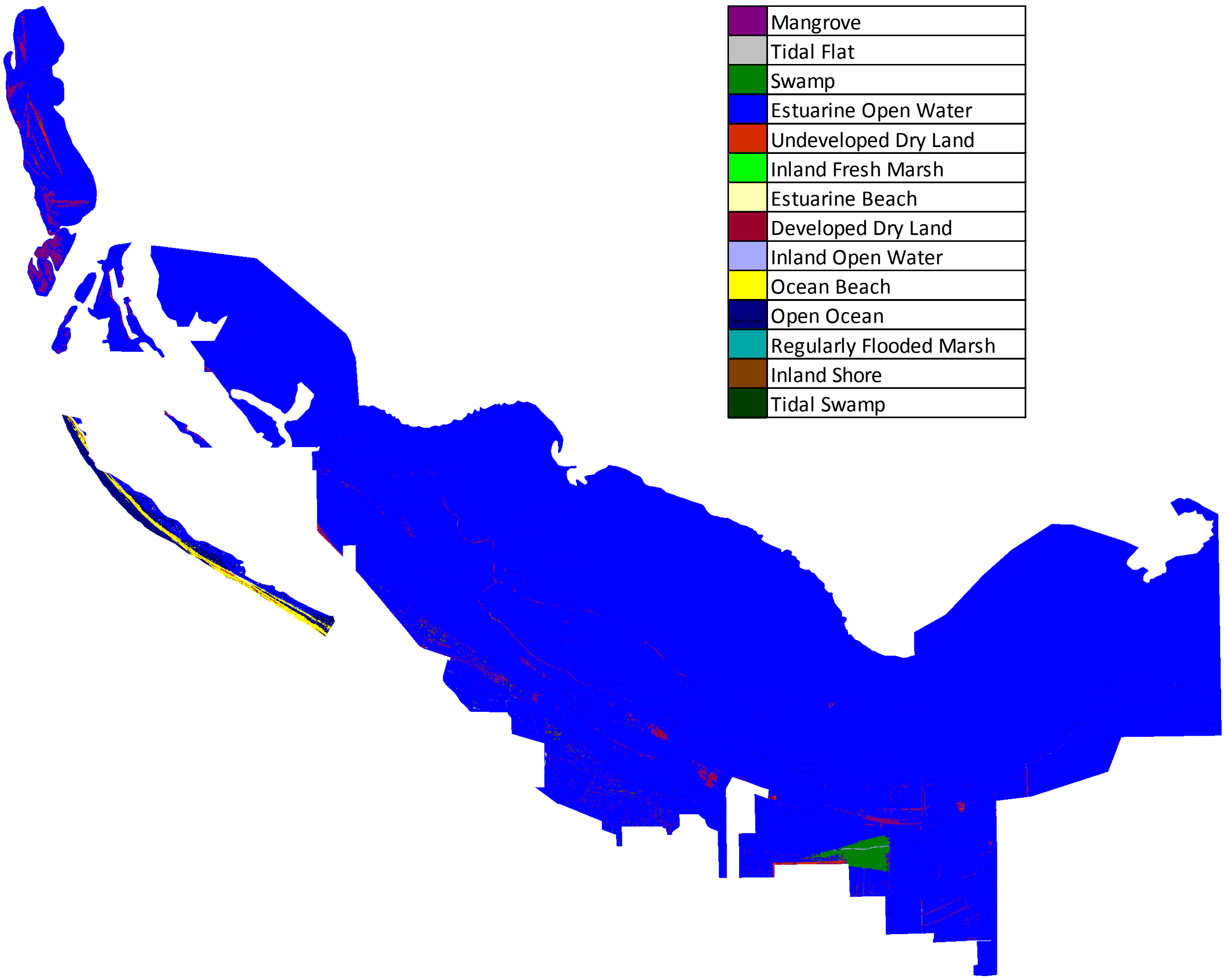
J.N. “Ding” Darling NWR, 2025, 2 m SLR by 2100.



J.N. "Ding" Darling NWR, 2050, 2 m SLR by 2100.



J.N. "Ding" Darling NWR, 2075, 2 m SLR by 2100.



J.N. "Ding" Darling NWR, 2100, 2 m SLR by 2100.

Road inundation projections

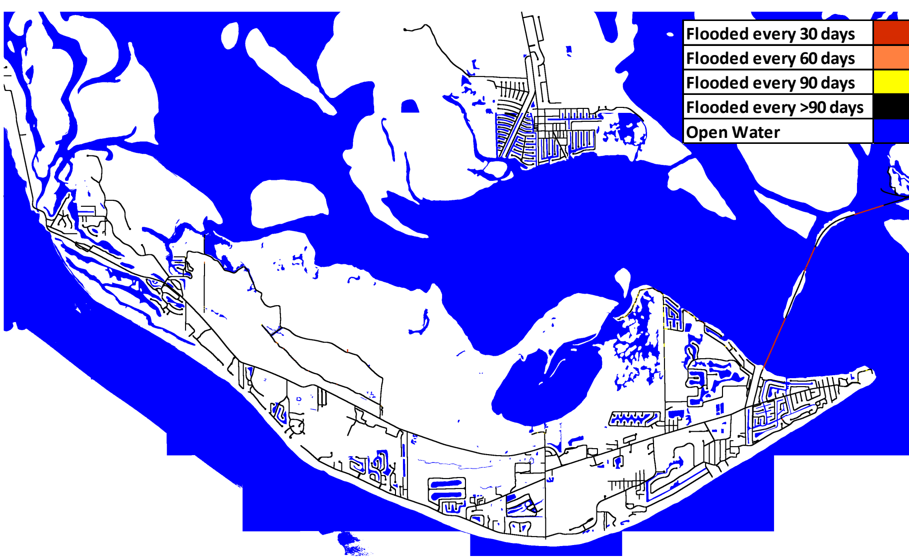
Increasing sea level is predicted to affect the frequency of inundation of the road system within the refuge. The total length and inundation frequency of refuge roads under the simulated SLR scenarios are summarized in Table 6.

Table 6. Predicted length of inundated roads by 2100 given simulated scenarios of eustatic SLR at J.N. "Ding" Darling NWR.

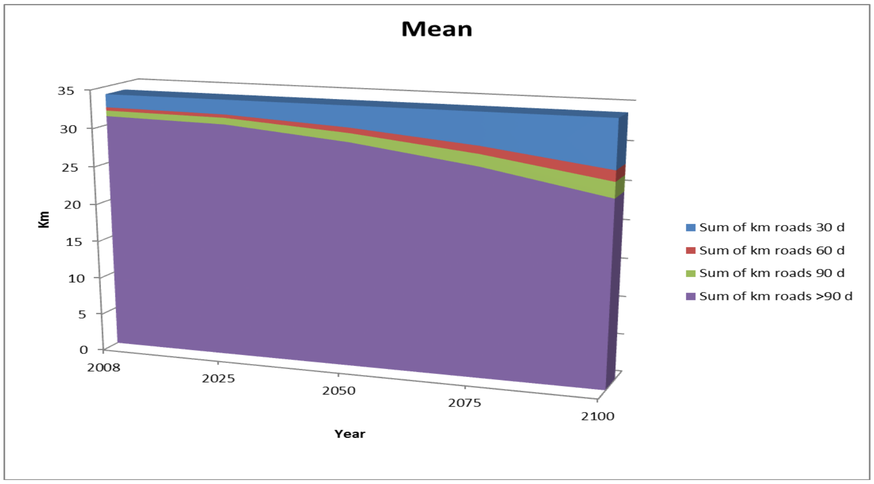
Inundation Frequency (days)	Initial coverage (km)	Total length of inundated roads by 2100 for different SLR scenarios (km)				
		0.39 m	0.69 m	1 m	1.5 m	2 m
<30 (most vulnerable)	1.7	6.3	15.7	26.6	33.2	34.0
30-60	0.4	1.4	2.0	1.6	0.2	0.0
60-90	0.7	2.0	2.7	1.3	0.2	0.0
>90 (least vulnerable)	31.1	24.3	13.6	4.5	0.4	0.0
total	34.0	34.0	34.0	34.0	34.0	34.0

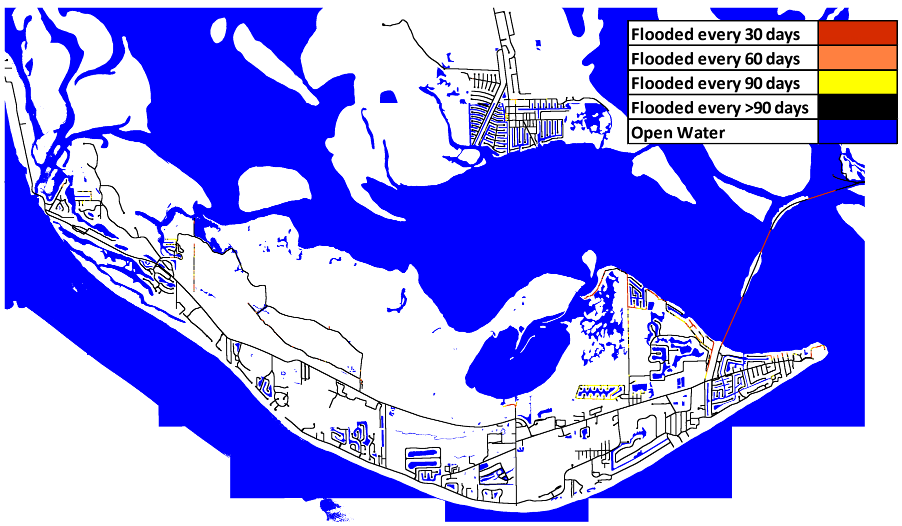
Of the total 34 km of roads today only a small fraction are inundated with a frequency of less than every 90 days. However, even under the most conservative scenario, by 2100 more than 28% of the total road lengths becomes inundated at least once every 3 months. Under the 2 m SLR, all the roads are predicted to be inundated by 2100 at least once every 30 days. The intermediate SLR scenarios have predictions that lie between these two extreme SLR scenarios.

For planning and management purposes it is also important to know the location and timing of when roads become more vulnerable to inundation. For the 0.39 m SLR by 2100, increased road inundation is predicted to essentially start only after 2075 while under the 2 m SLR scenario by 2100, already between 2025 and 2050 a high proportion of roads with lower elevations are predicted to be inundated at least once every 30 days. The timing of the intermediate SLR scenarios is within 2025 and 2075 depending how high SLR rate is. The below maps and graphs presents the results in more details.

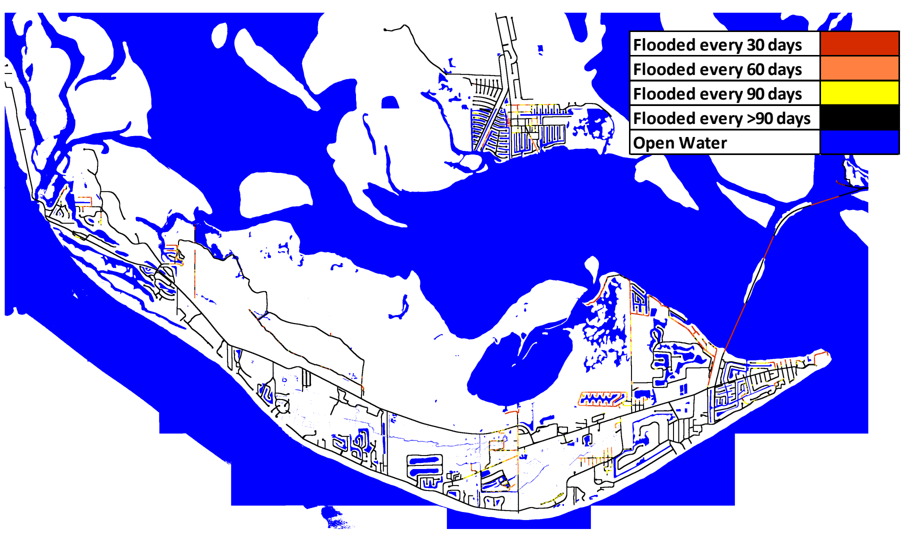


J.N. "Ding" Darling NWR, Road Inundation, Initial conditions

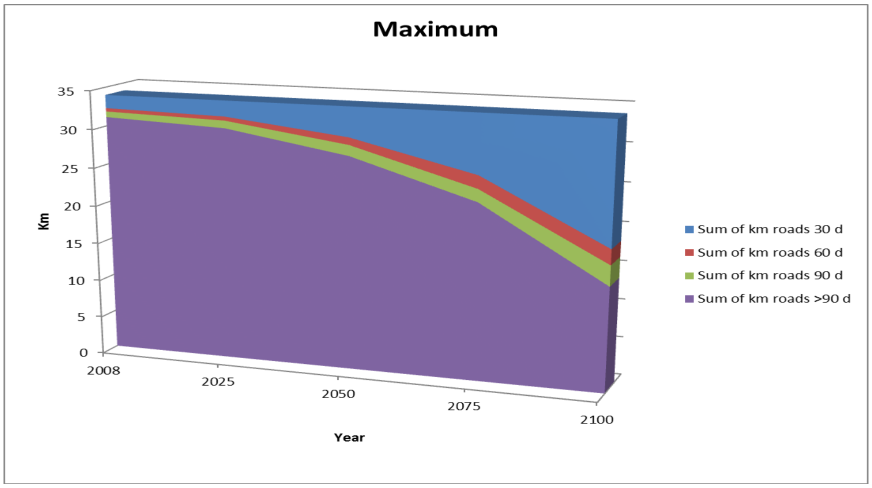


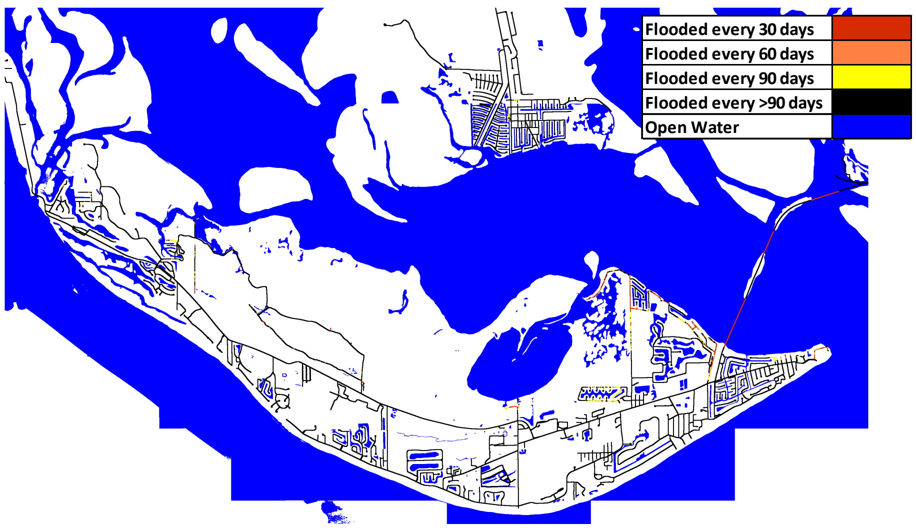


J.N. "Ding" Darling NWR, Road Inundation, 0.39 m SLR by 2100, 2075.

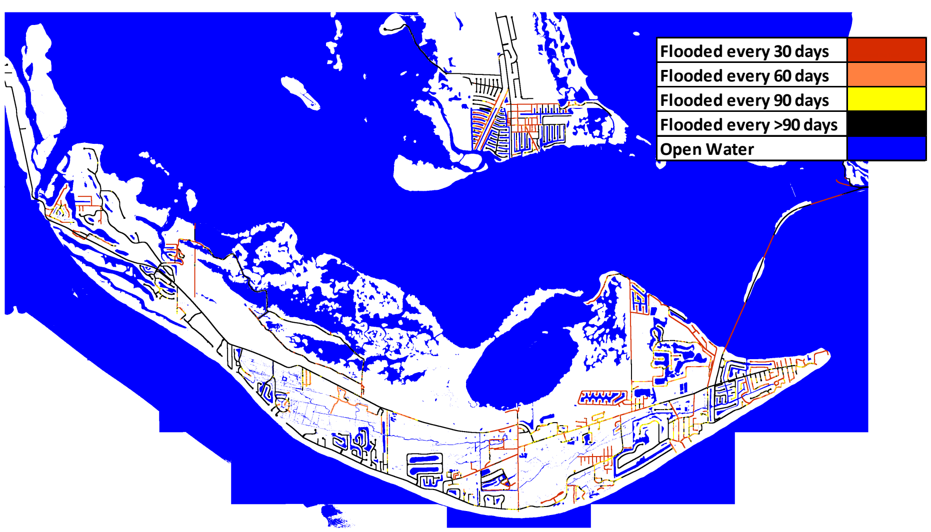


J.N. "Ding" Darling NWR, Road Inundation, 0.39 m SLR by 2100, 2100.

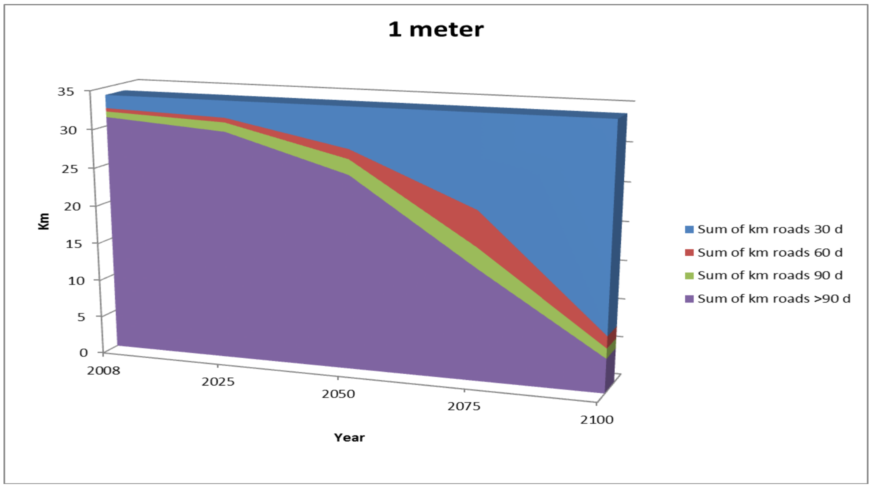




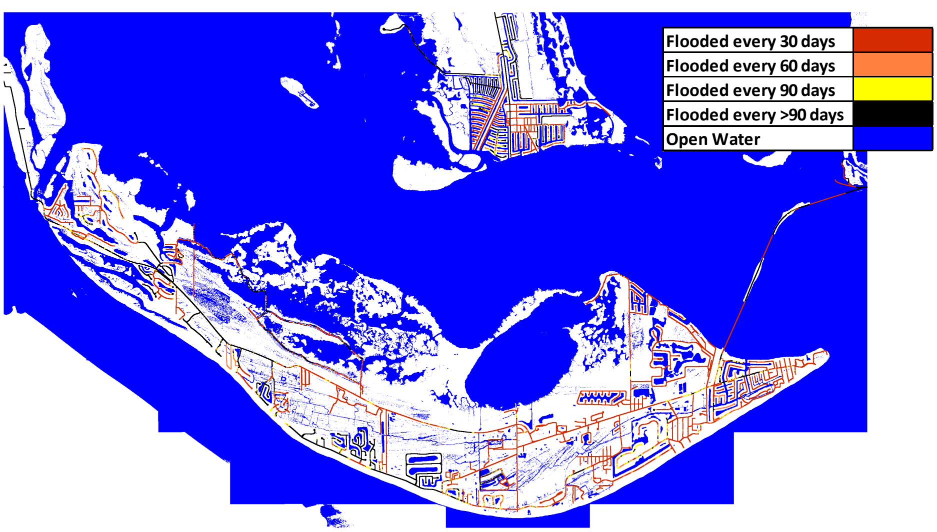
J.N. "Ding" Darling NWR, Road Inundation, 0.69 m SLR by 2100, 2050.



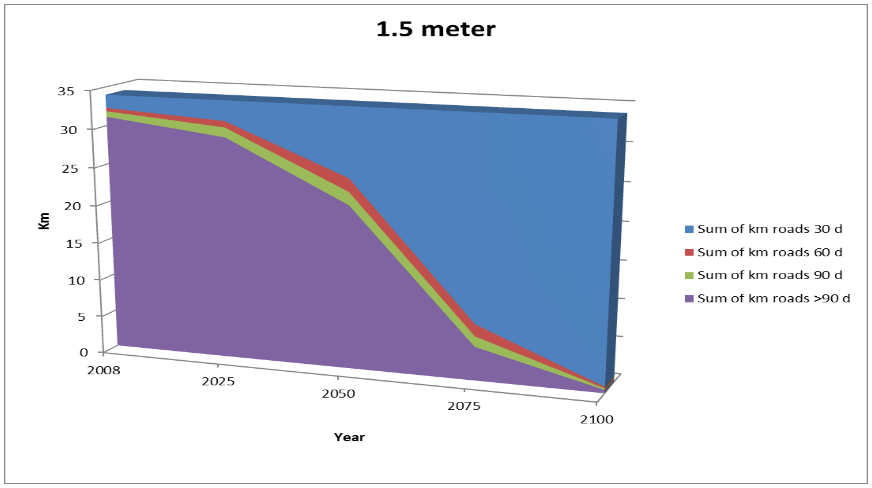
J.N. "Ding" Darling NWR, Road Inundation, 0.69 m SLR by 2100, 2100.

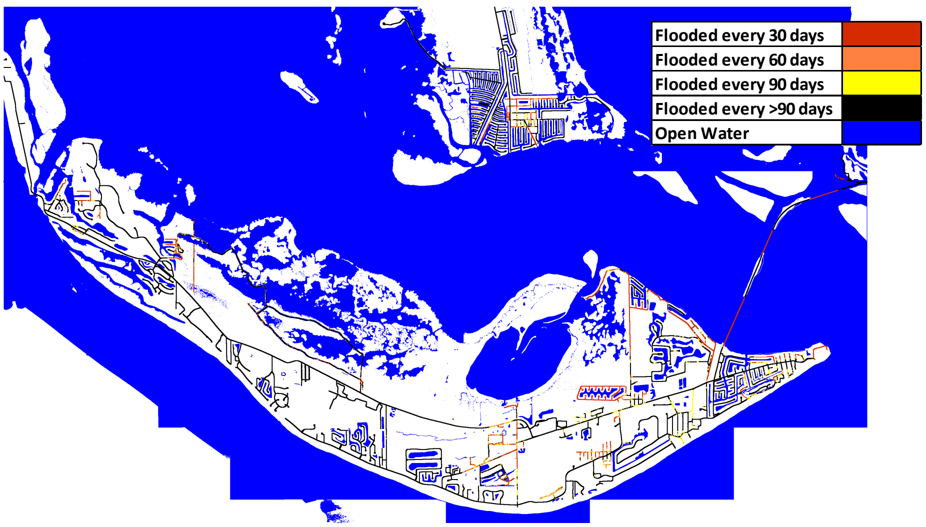


J.N. "Ding" Darling NWR, Road Inundation, 1 m SLR by 2100, 2050.

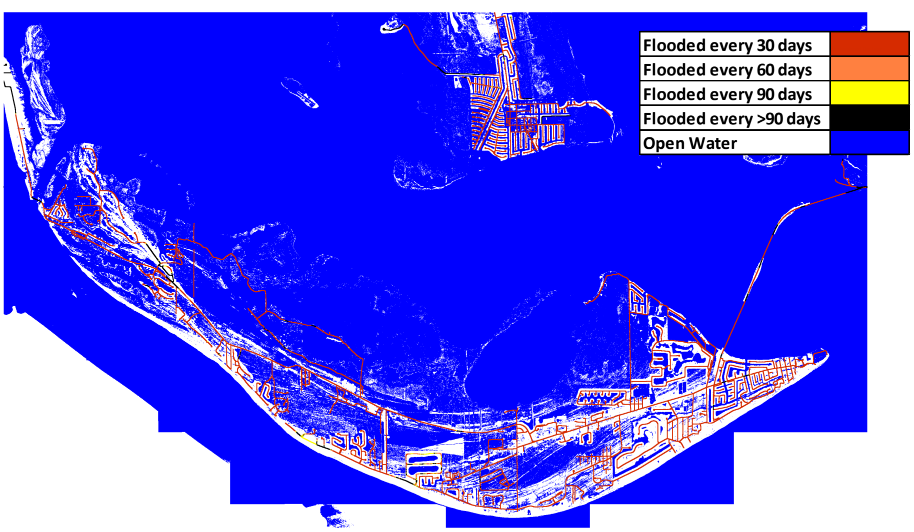


J.N. "Ding" Darling NWR, Road Inundation, 1 m SLR by 2100, 2100.

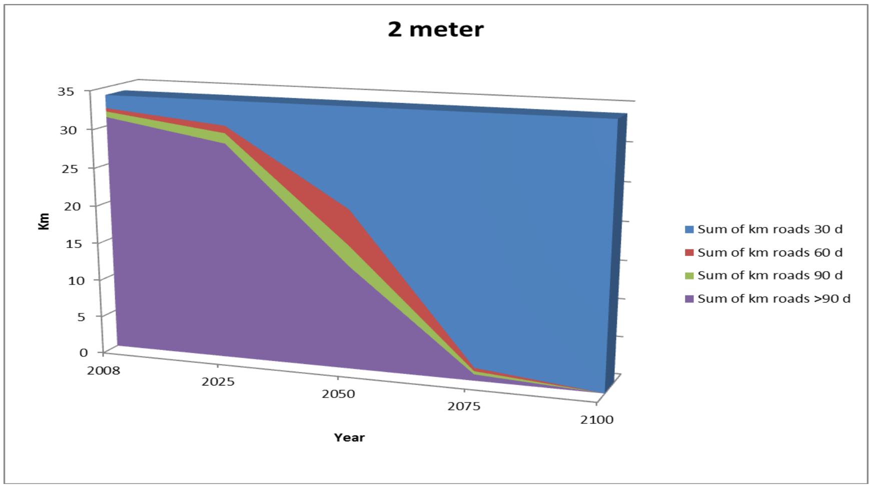


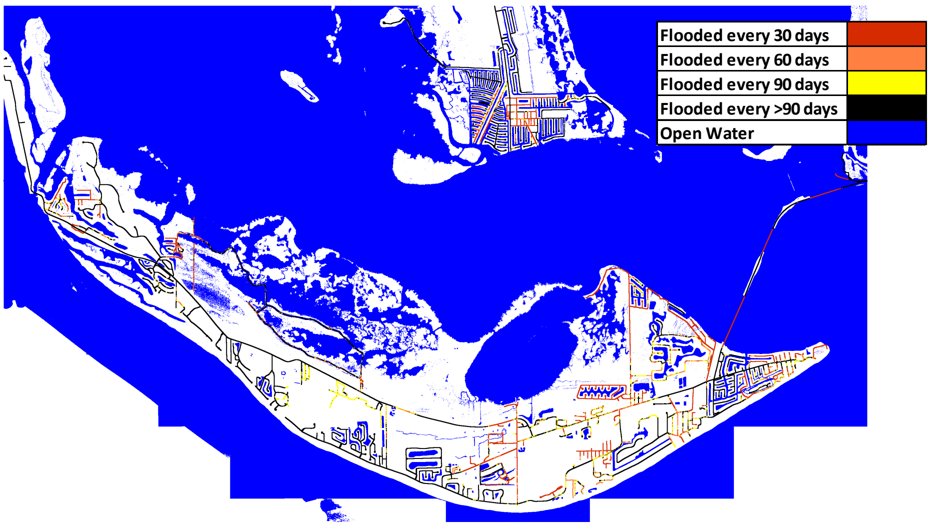


J.N. "Ding" Darling NWR, Road Inundation, 1.5 m SLR by 2100, 2050.

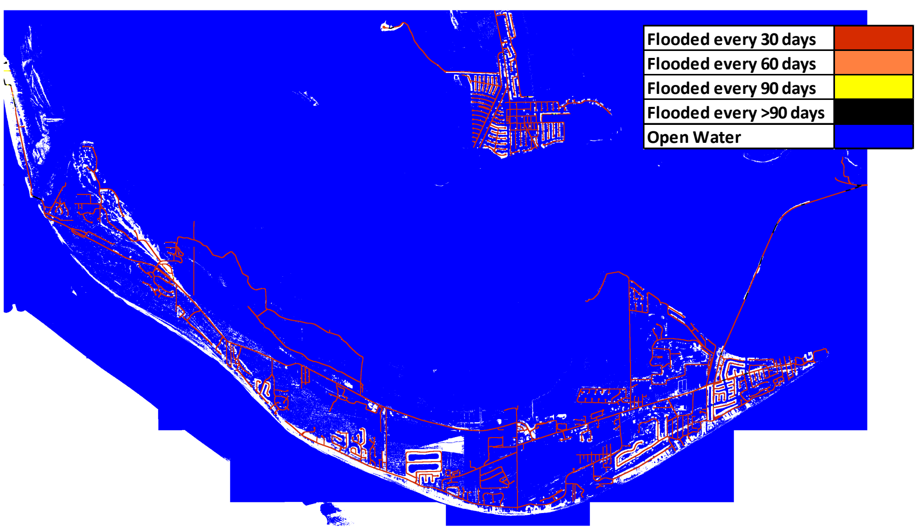


J.N. "Ding" Darling NWR, Road Inundation, 1.5 m SLR by 2100, 2100.





J.N. "Ding" Darling NWR, Road Inundation, 2 m SLR by 2100, 2050.



J.N. "Ding" Darling NWR, Road Inundation, 2 m SLR by 2100, 2100.

Discussion

Model results for J.N. 'Ding' Darling NWR indicate that it is vulnerable to sea-level rise under all scenarios examined. Accounting for road infrastructure enabled us to study road vulnerability and also had minor effects on wetland predictions, especially with regards to inland-fresh marshes.

Mangroves, which make up the majority of the refuge, are predicted to increase their area of coverage when the rate of SLR is lower than the accretion rate applied. However, considerable losses of mangroves are predicted when the rate of SLR exceeds the 7 mm/year.

Although it makes up only a small part of the refuge, the inland–fresh marsh is predicted to be severely impacted under each SLR scenario. However, when accounting for road elevations, some inland-fresh marshes are slightly more resilient than in previous simulations, as the surrounding roads act as protecting dikes. Despite this, for SLR exceeding 0.69 m SLR by 2100, water levels become high enough to overtop these roads and practically all of this wetland type is predicted to be lost by 2100.

The roads present in this refuge are predicted to be inundated more frequently under all SLR scenarios studied with impacts occurring earlier under higher SLR scenarios.

A primary requirement for producing reliable results using SLAMM is the use of high-quality elevation data. This analysis was run using LiDAR data, which reduces uncertainty in the model results to some degree. However, at this site accretion rates provide an additional important source of model uncertainty. There were no local accretion data available in the literature; therefore SLAMM default values were applied. Specific measurements of accretion rates within the refuge could provide better predictions of marsh losses in the future.

While data-layer updates have considerably improved the SLAMM projections reported here, input layers, parameter inputs (as mentioned above), and the conceptual model continue to have uncertainties that should be kept in mind when interpreting these results. Perhaps most importantly, the extent of future sea-level rise is unknown, as are the drivers of climate change used by scientists when projecting SLR rates. Future levels of economic activity, fuel type (e.g., fossil or renewable, etc.), fuel consumption, and greenhouse gas emissions are unknown and estimates of these driving variables are speculative. To account for these uncertainties, results presented here investigated effects for a wide range of possible sea level rise scenarios, from a more conservative rise (0.39 m by 2100) to a more accelerated process (2 m by 2100). To better support managers and decision-makers, the results presented here could be studied as a function of input-data uncertainty to provide a range of possible outcomes and their likelihood.

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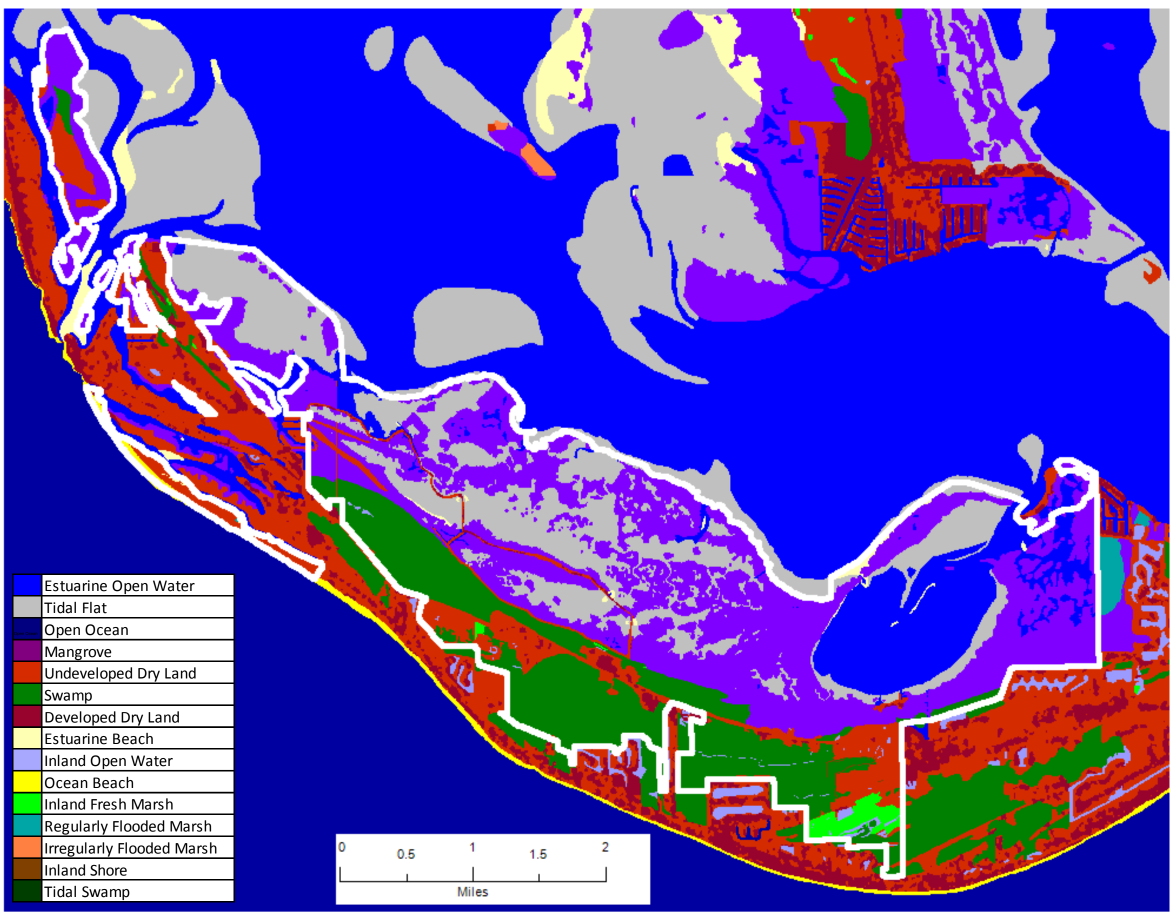
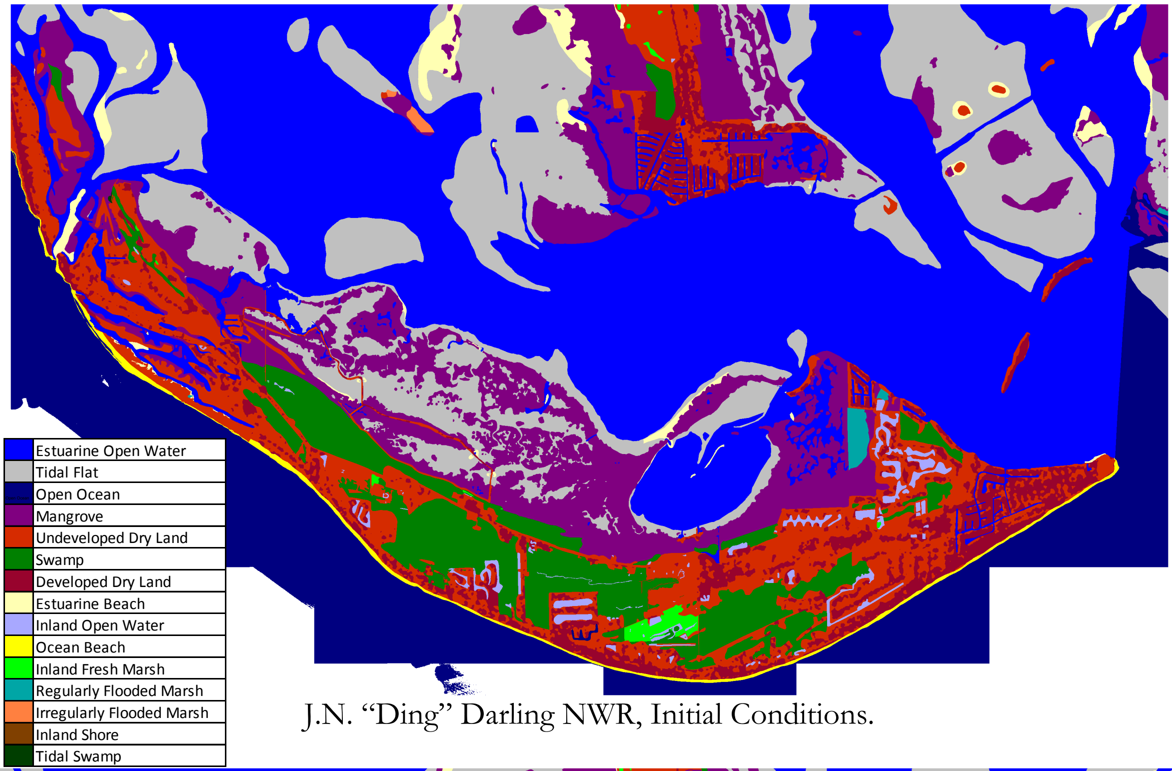
Appendix A: Contextual Results

The SLAMM model does take into account the context of the surrounding lands or open water when calculating effects. For example, erosion rates are calculated based on the maximum fetch (wave action) which is estimated by assessing contiguous open water to a given marsh cell. Another example is that inundated dry lands will convert to marshes or ocean beach depending on their proximity to open ocean. Therefore, an area larger than the boundaries of the USFWS refuge was modeled. Maps of these results are presented here with the following caveats:

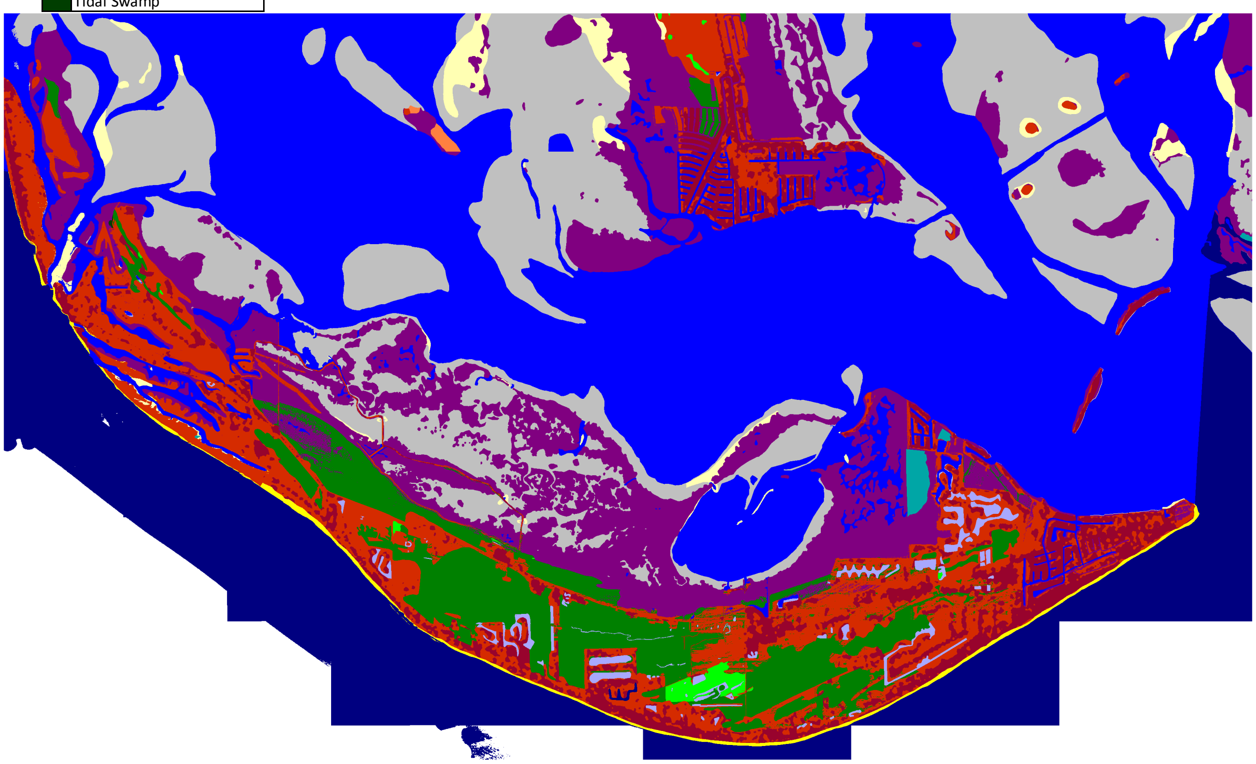
- Results were critically examined within USFWS refuges but not closely examined for the larger region.
- Site-specific parameters for the model were derived for USFWS refuges whenever possible and may not be regionally applicable.
- Especially in areas where dikes are present, an effort was made to assess the probable location and effects of dikes for USFWS refuges, but this effort was not made for surrounding areas.



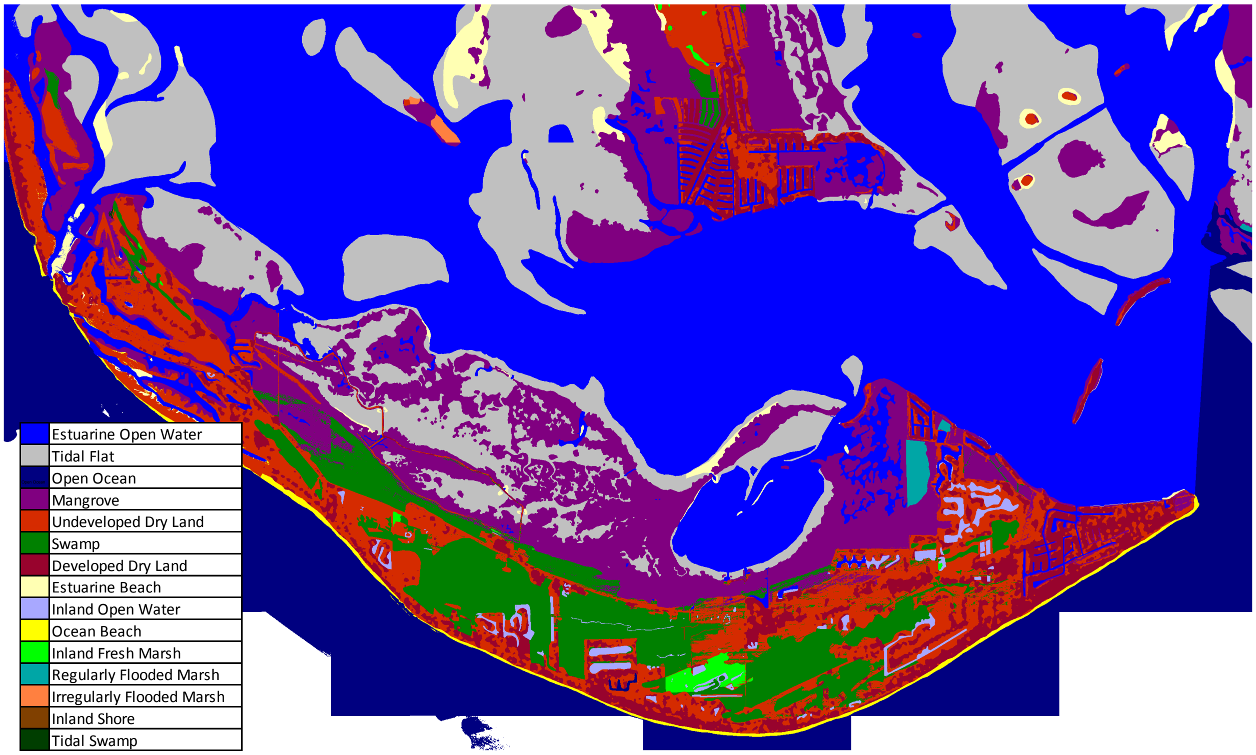
J.N. "Ding" Darling National Wildlife Refuge within simulation context (white).



J.N. "Ding" Darling NWR, Initial Conditions.



J.N. "Ding" Darling NWR, 2025, Scenario A1B Mean, 0.39 m SLR by 2100.



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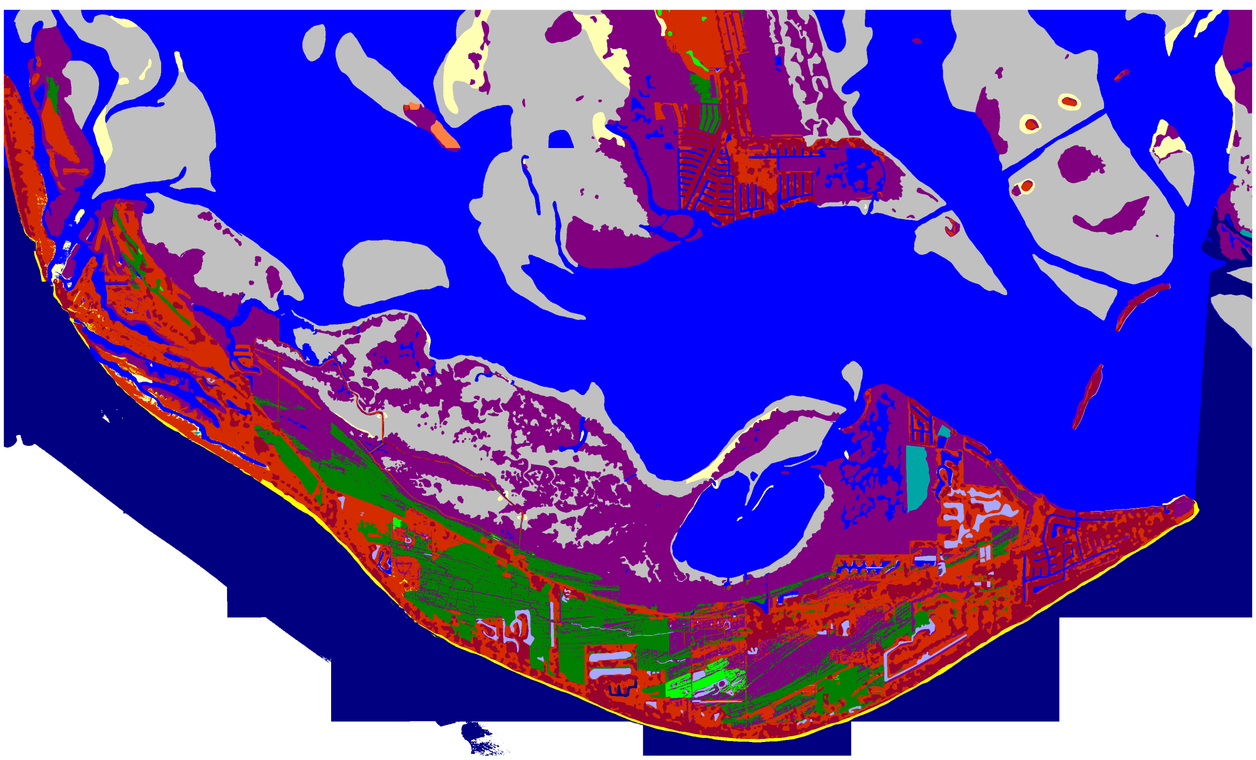

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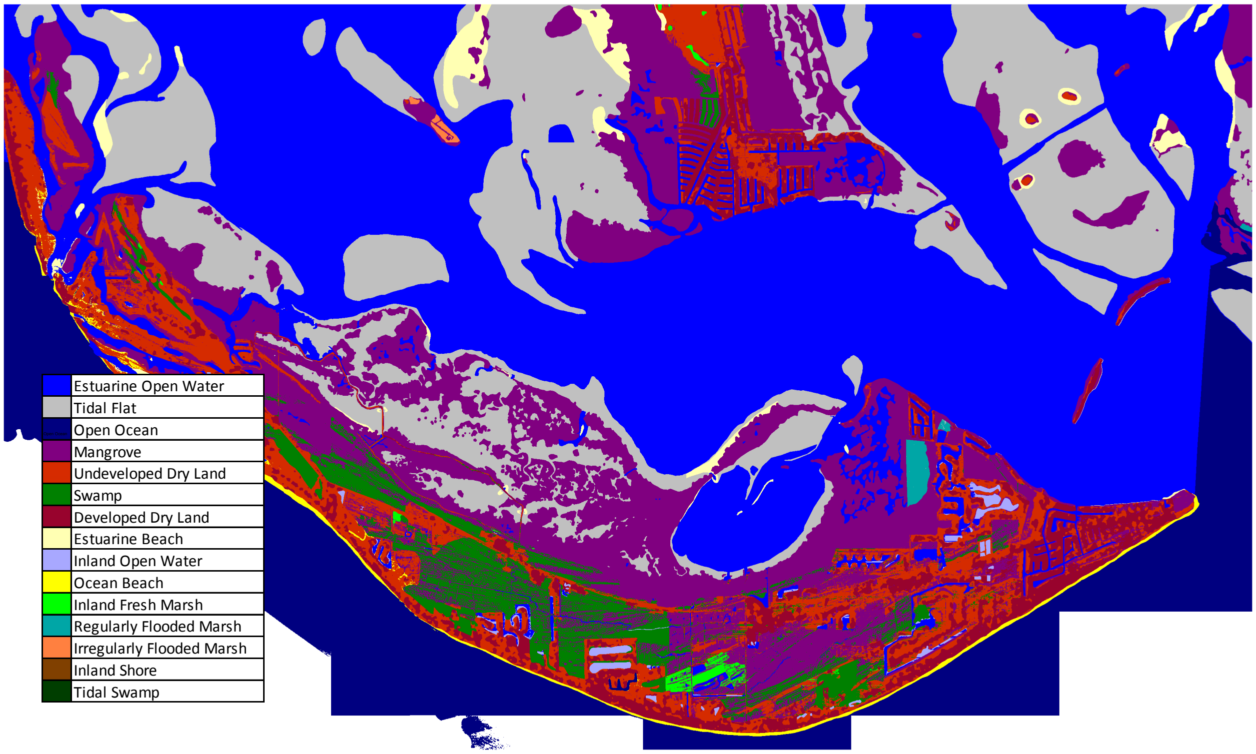
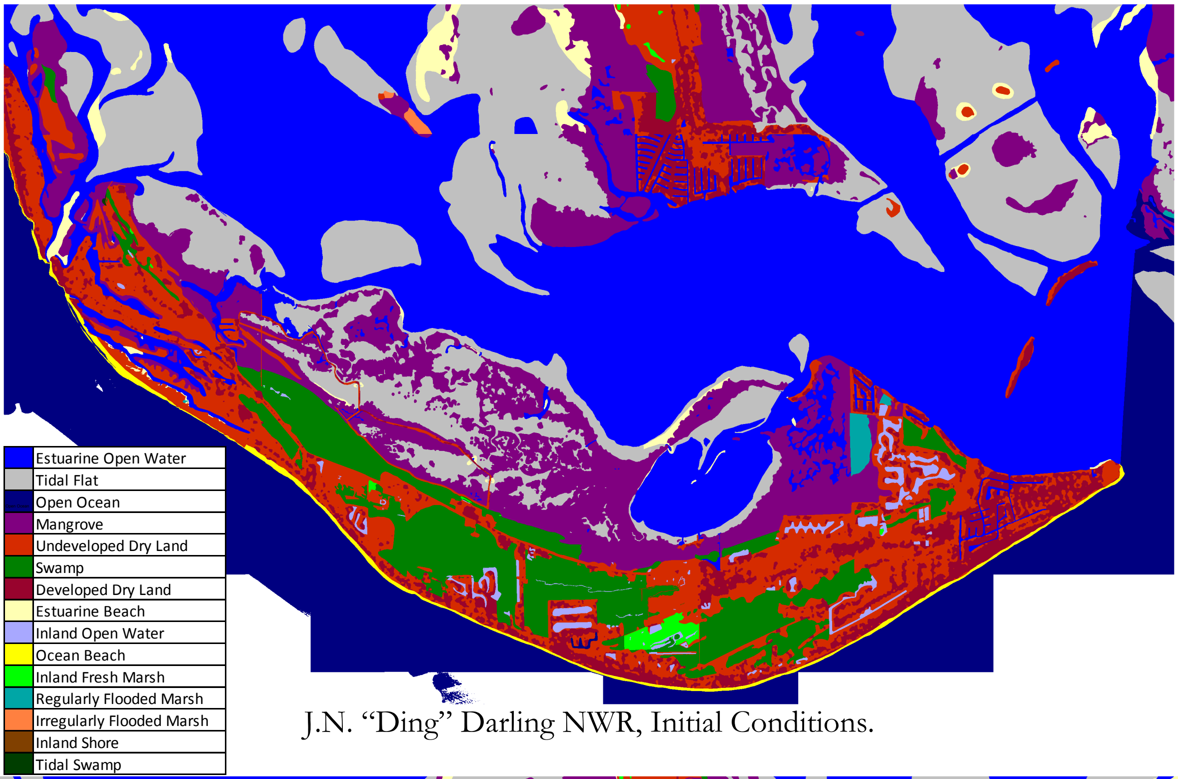
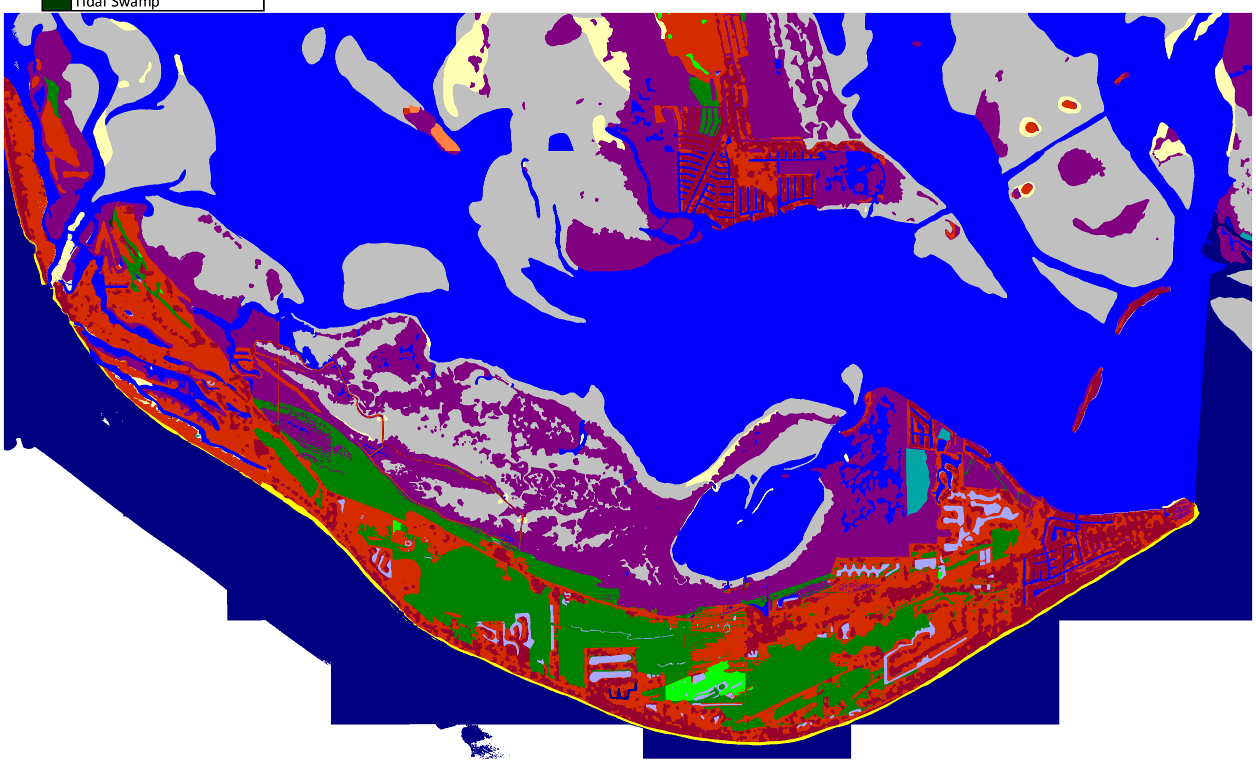


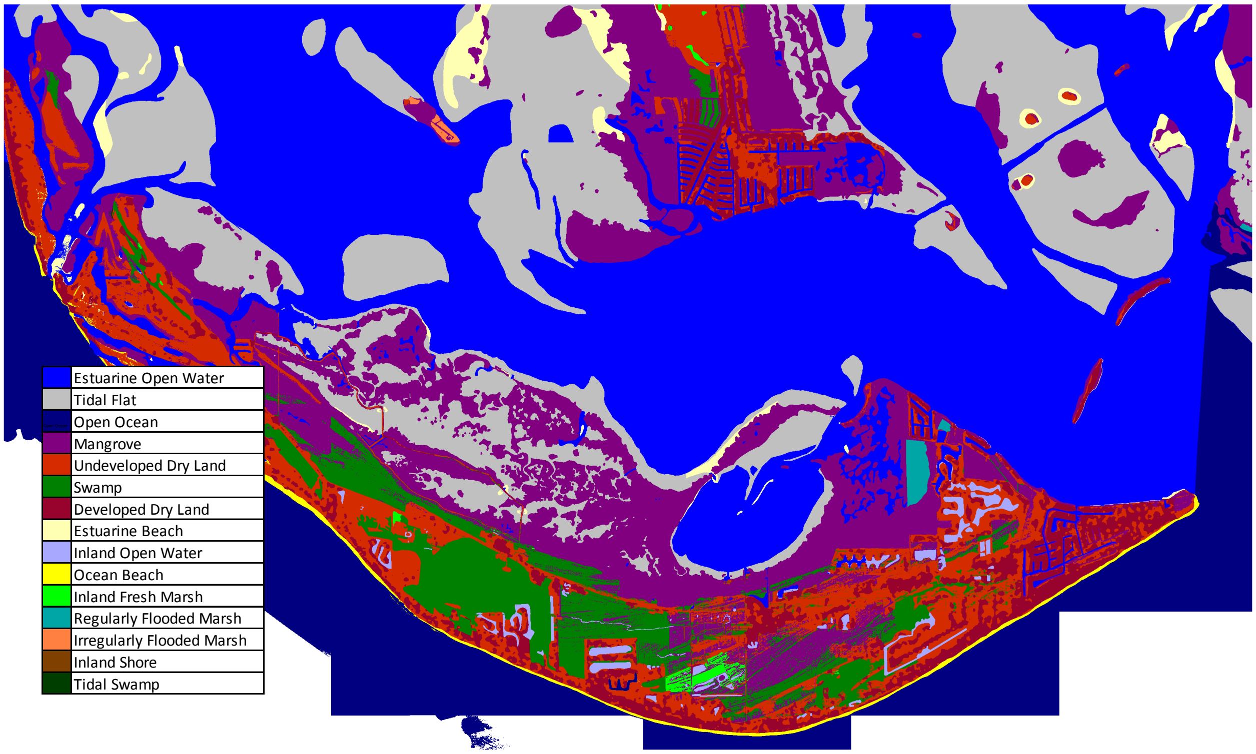
J.N. "Ding" Darling NWR, 2100, Scenario A1B Mean, 0.39 m SLR by 2100.



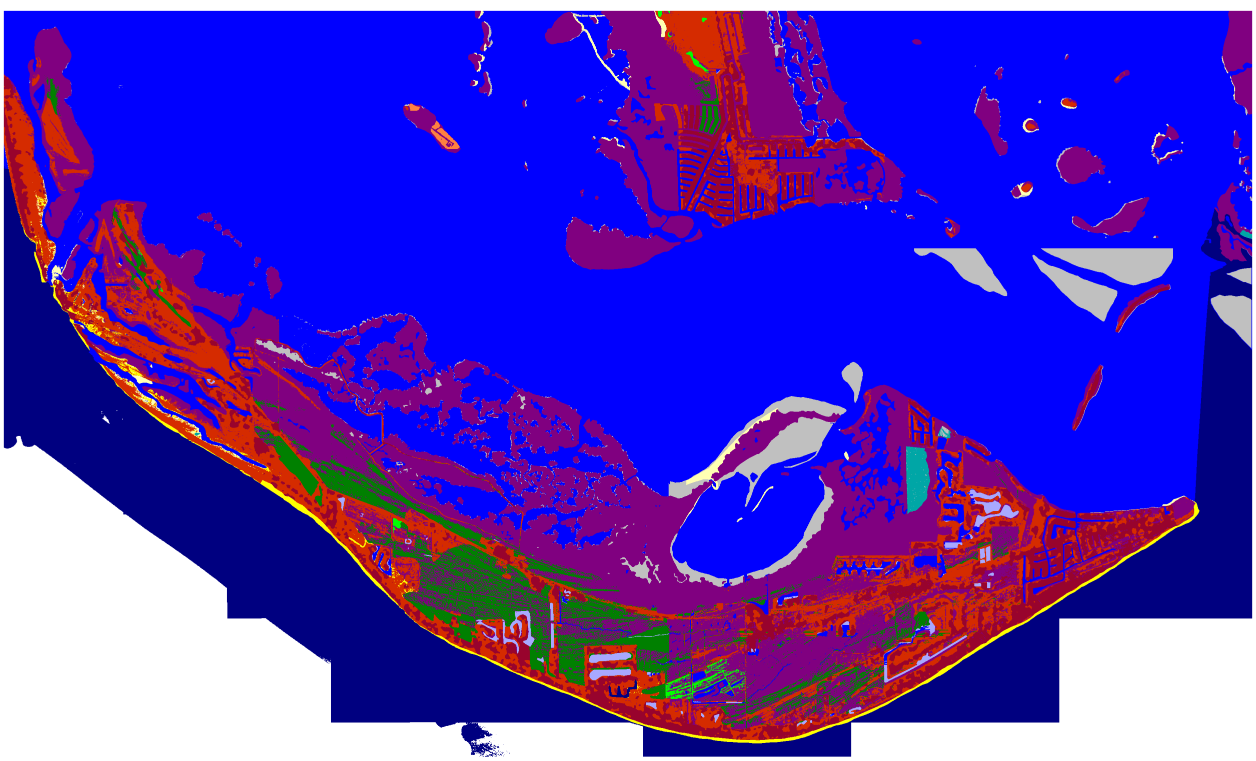
J.N. “Ding” Darling NWR, Initial Conditions.



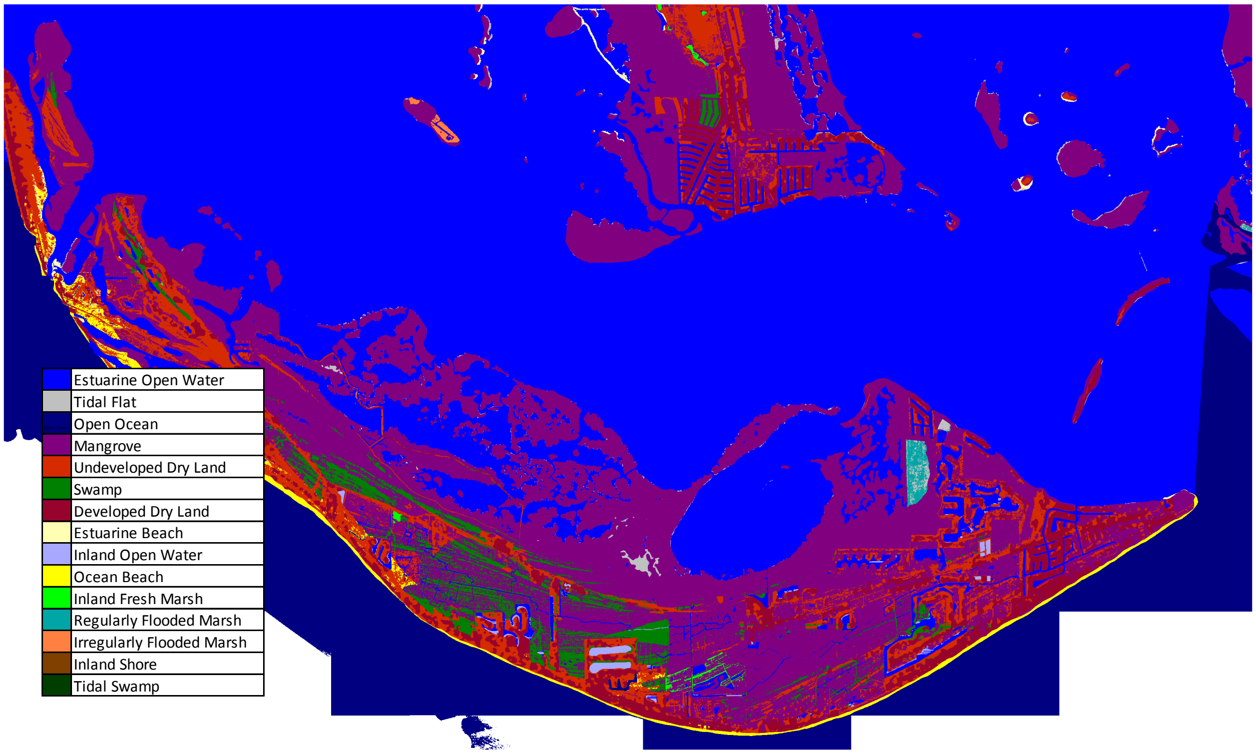
J.N. “Ding” Darling NWR, 2025, Scenario A1B Maximum, 0.69 m SLR by 2100.



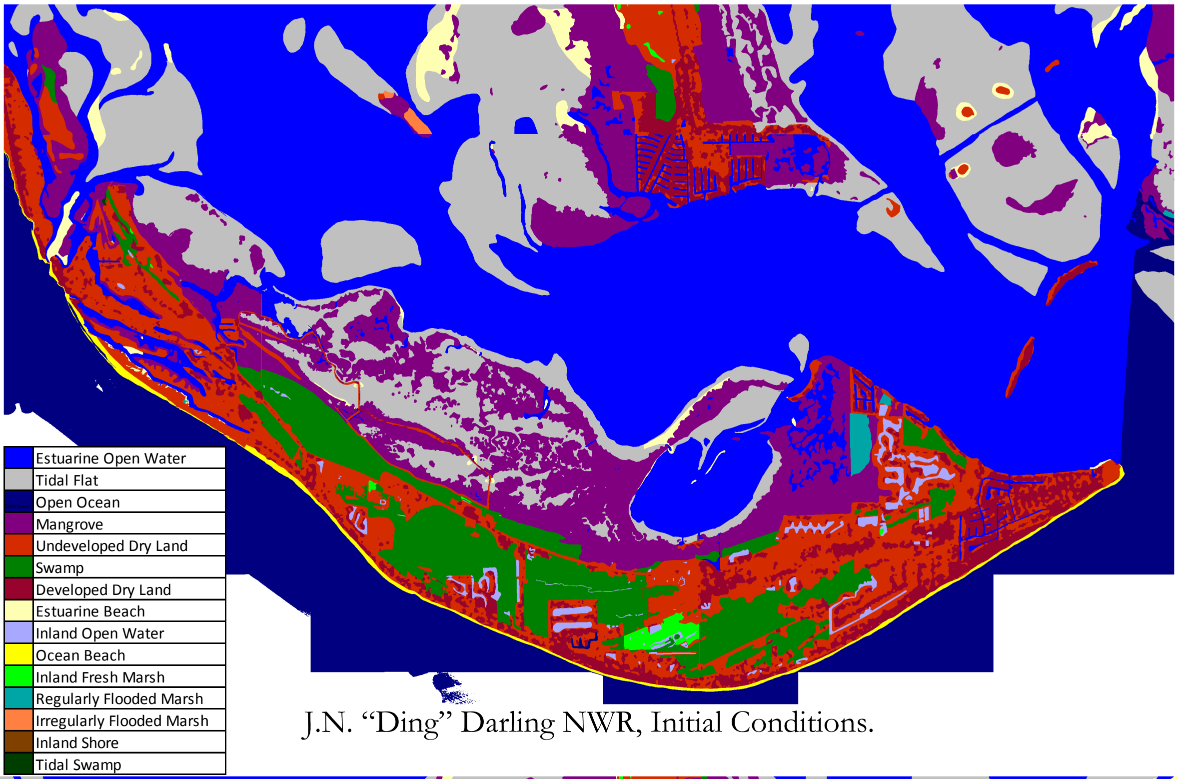
J.N. "Ding" Darling NWR, 2050, Scenario A1B Maximum, 0.69 m SLR by 2100.



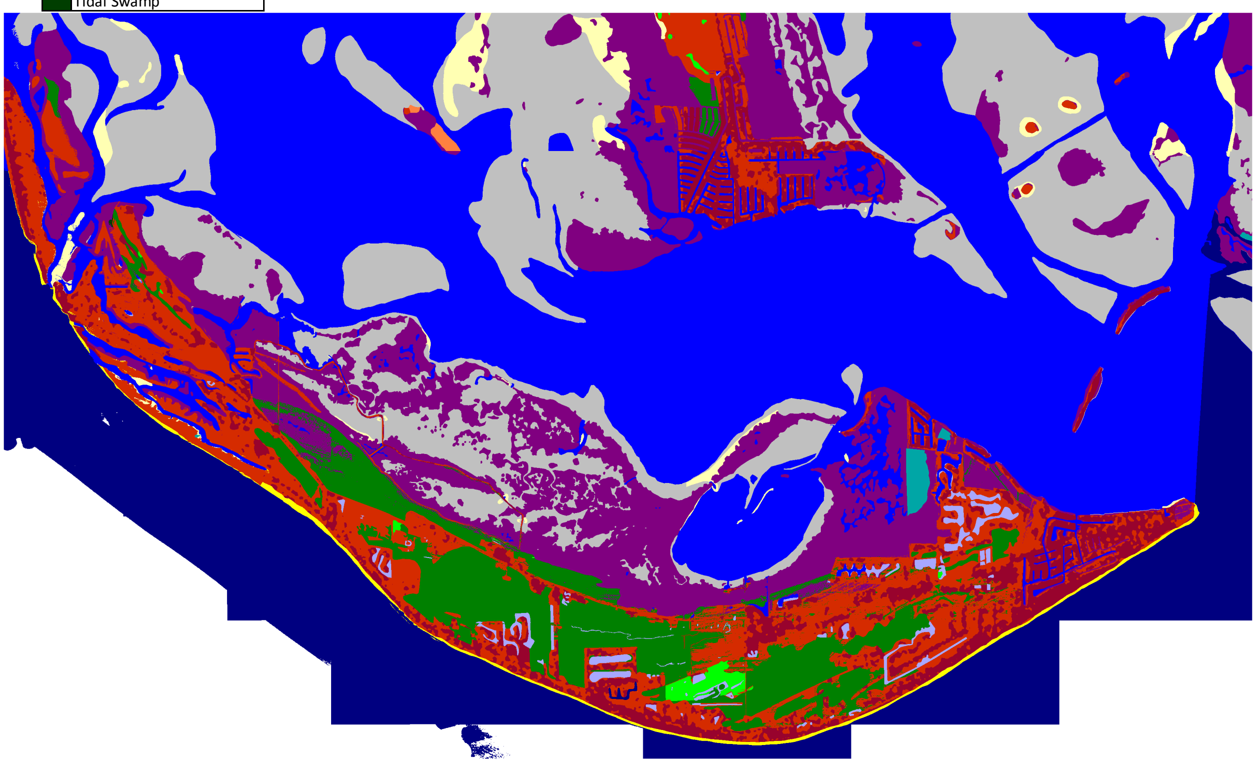
J.N. "Ding" Darling NWR, 2075, Scenario A1B Maximum, 0.69 m SLR by 2100.



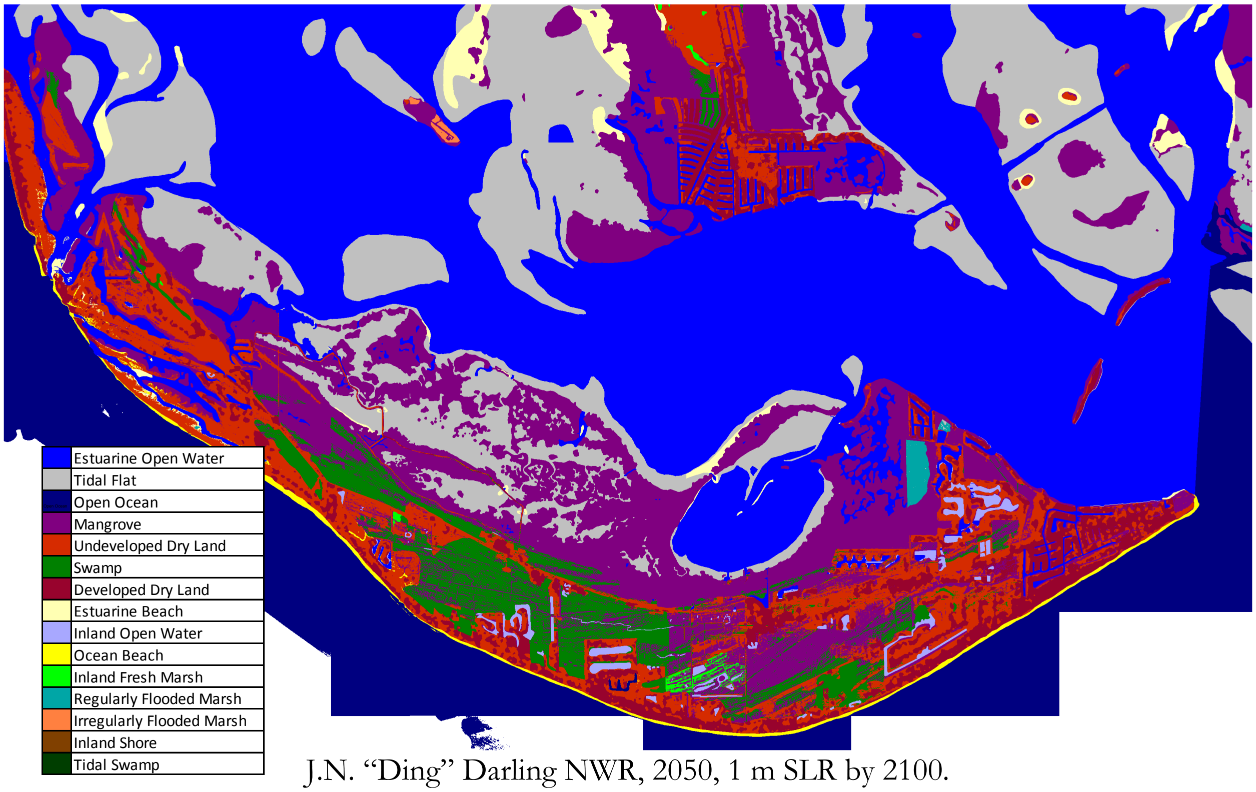
J.N. "Ding" Darling NWR, 2100, Scenario A1B Maximum, 0.69 m SLR by 2100.



J.N. "Ding" Darling NWR, Initial Conditions.



J.N. "Ding" Darling NWR, 2025, 1 m SLR by 2100.



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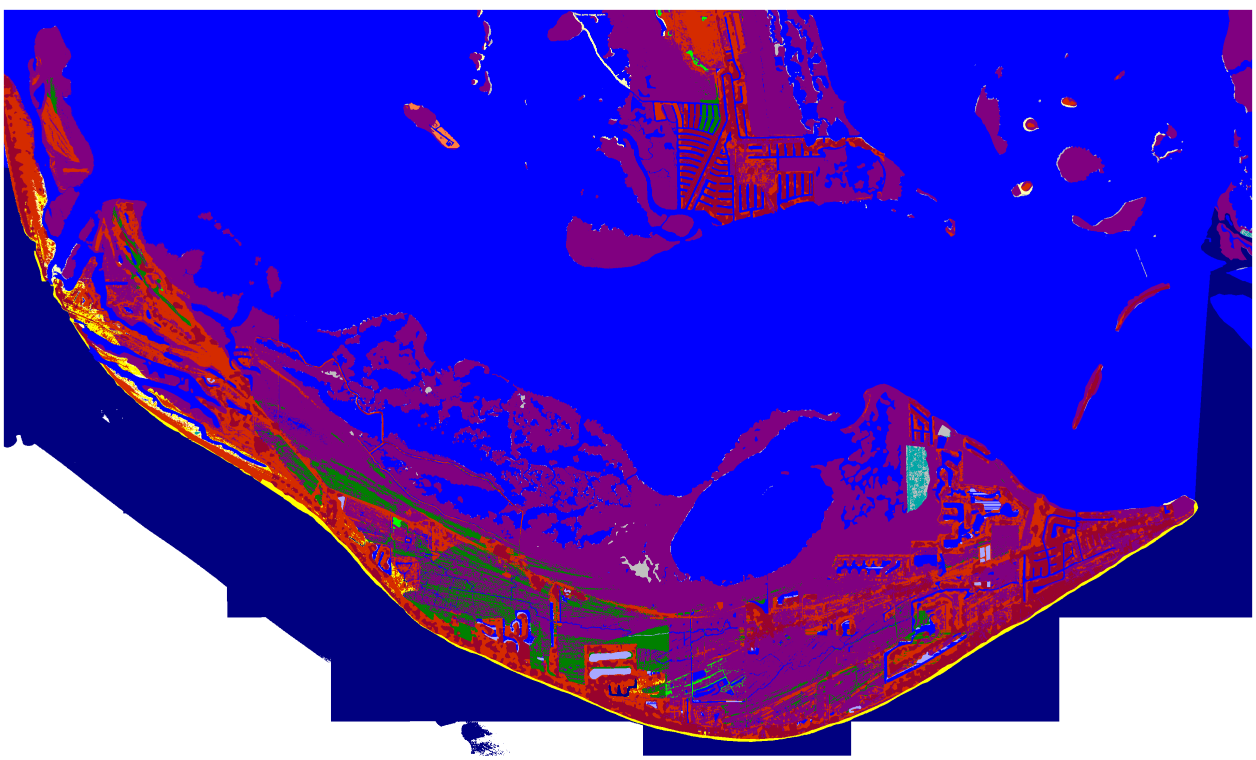

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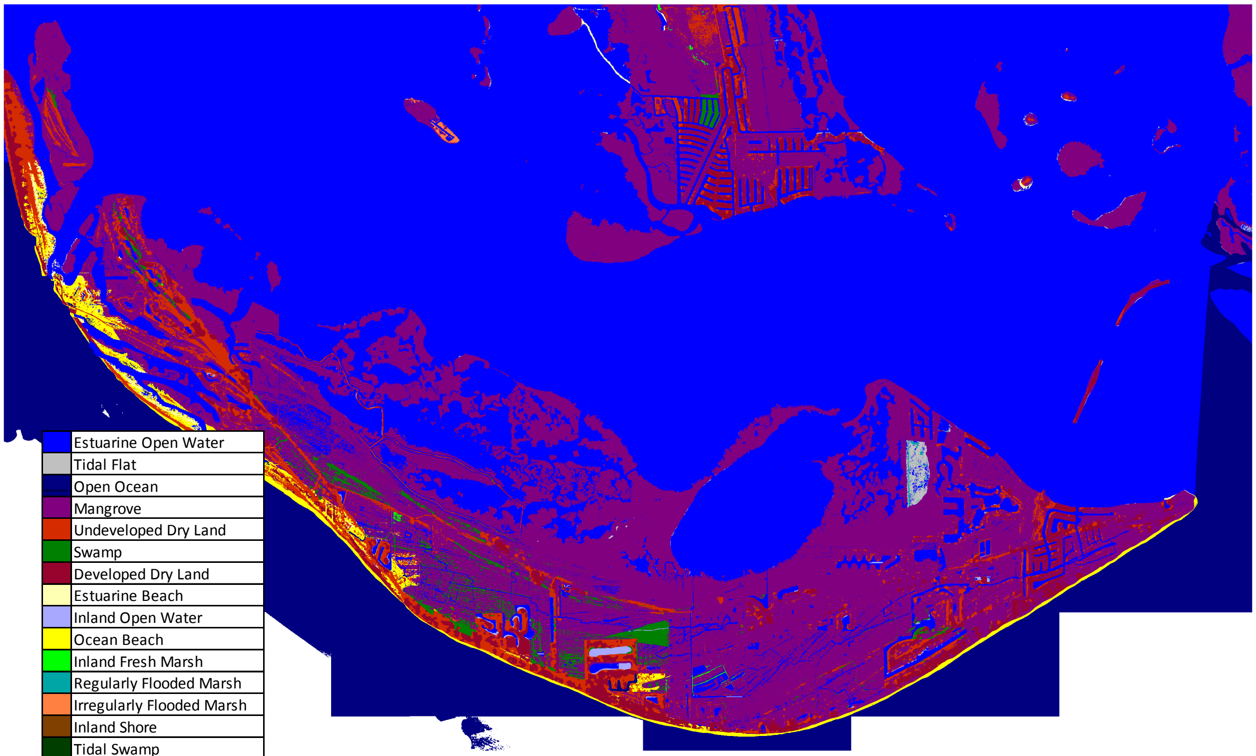

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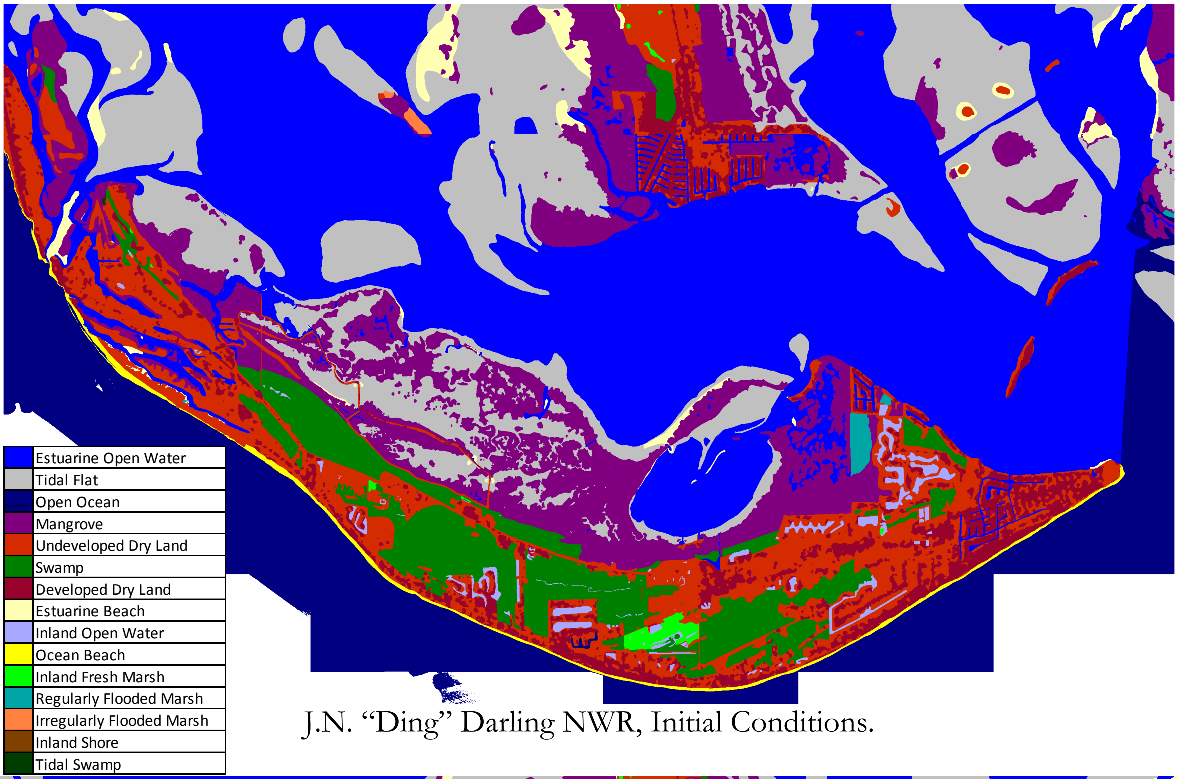
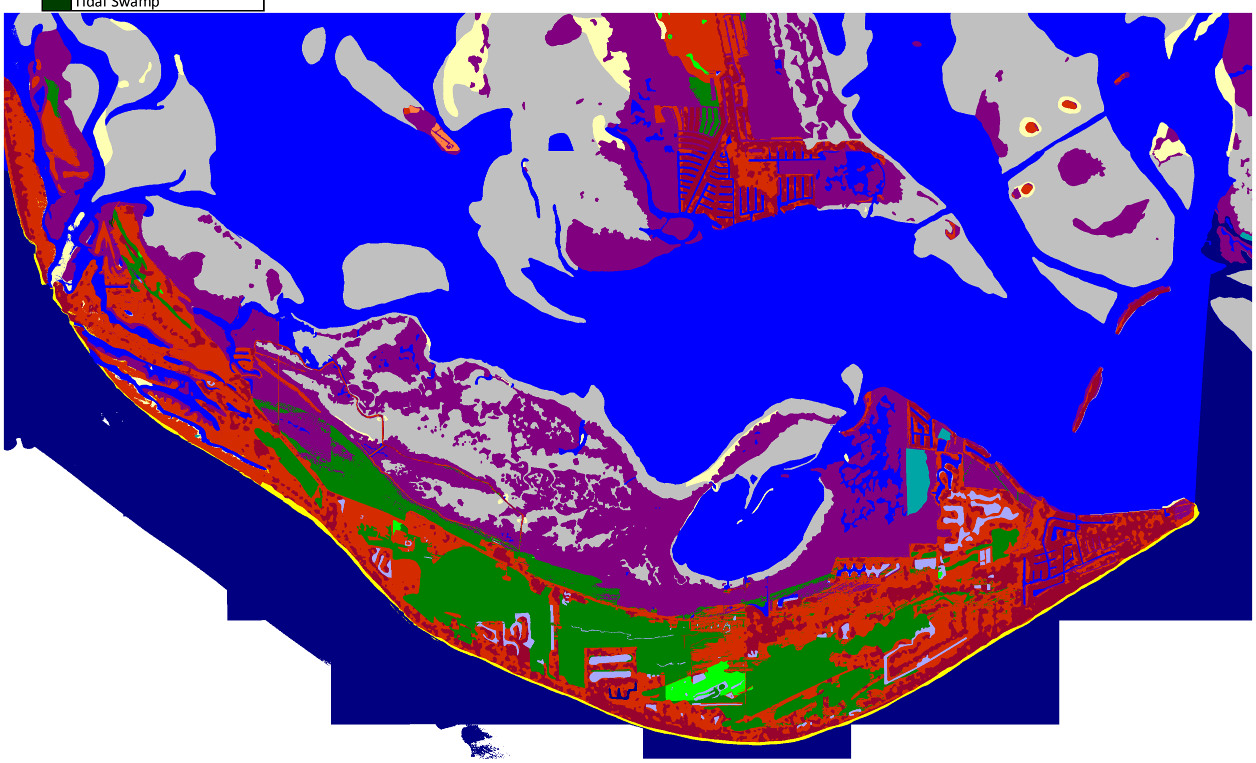


J.N. "Ding" Darling NWR, Initial Conditions.



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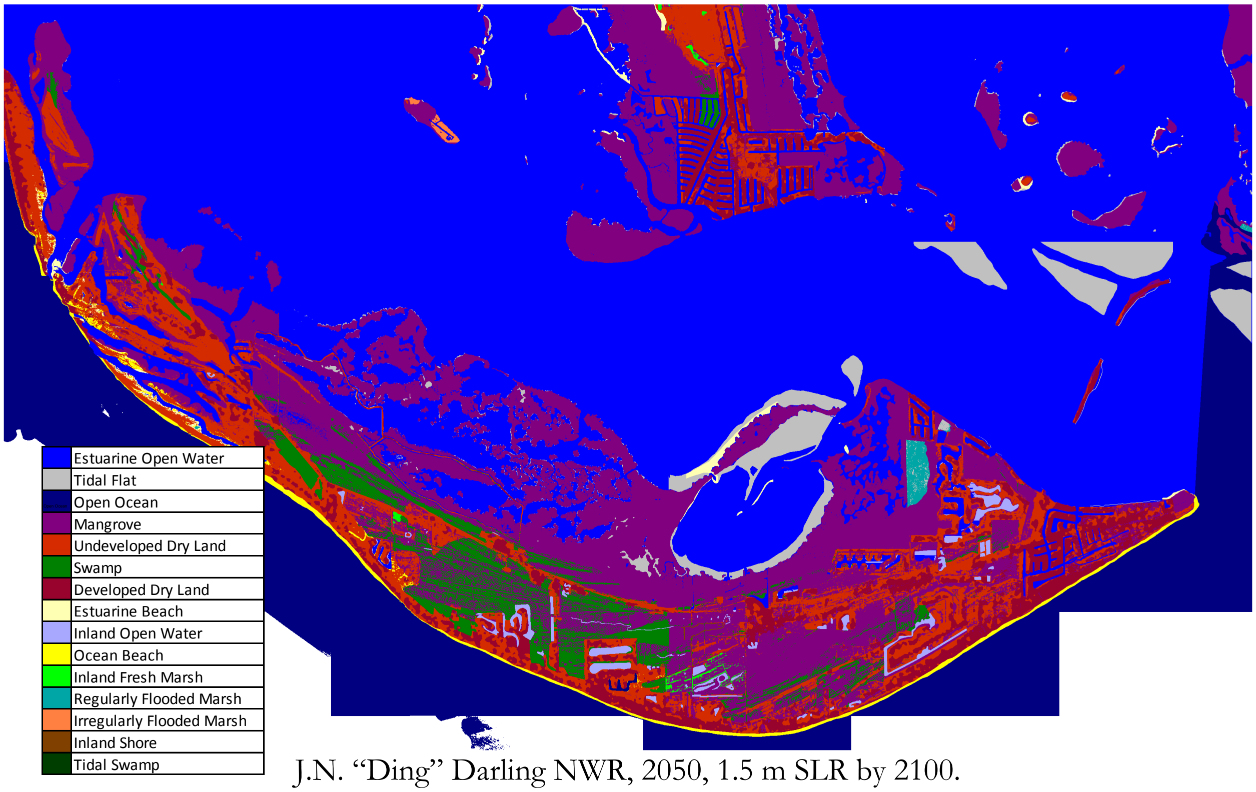

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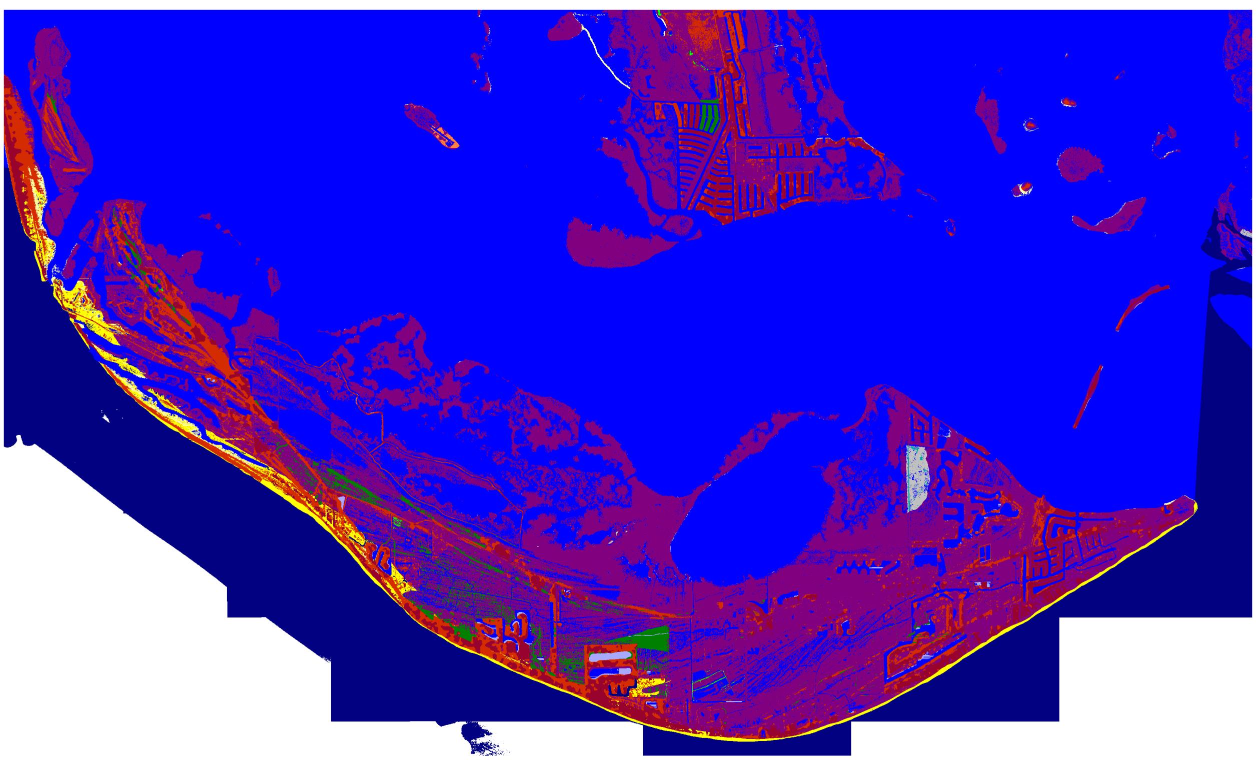

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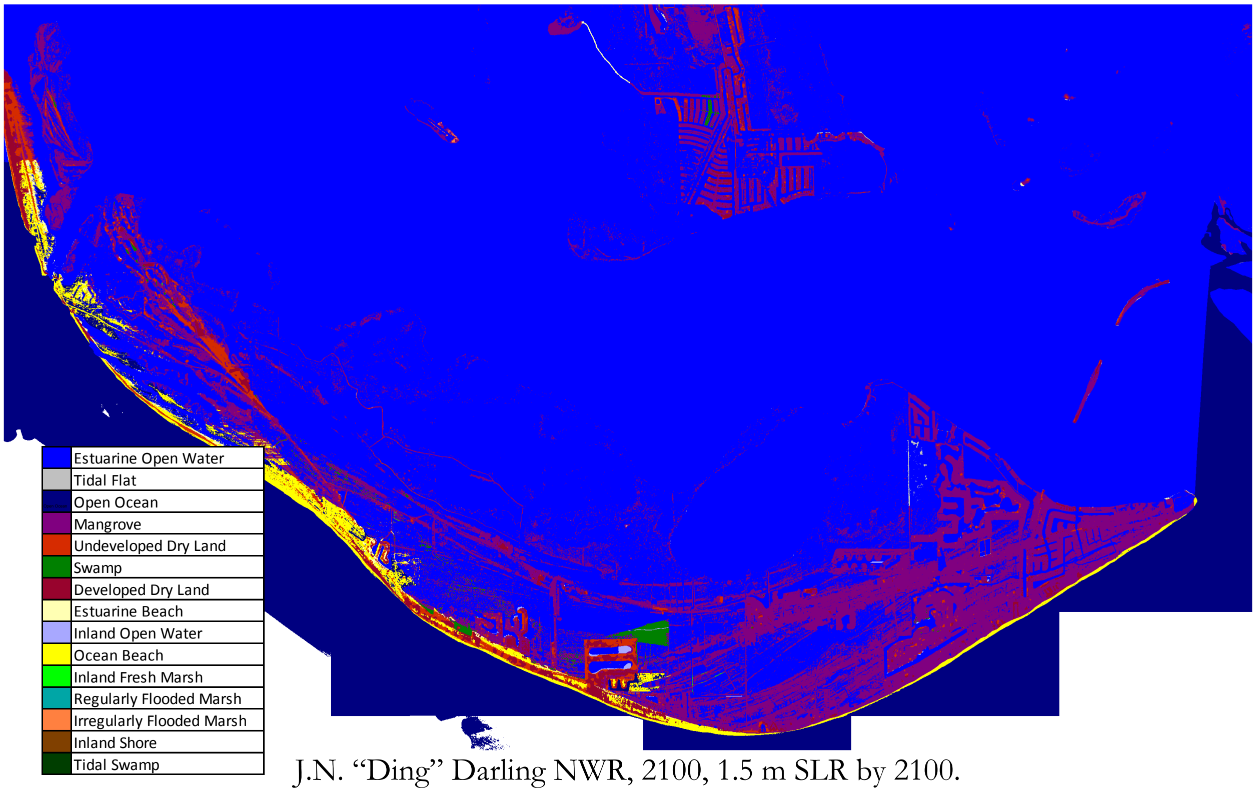

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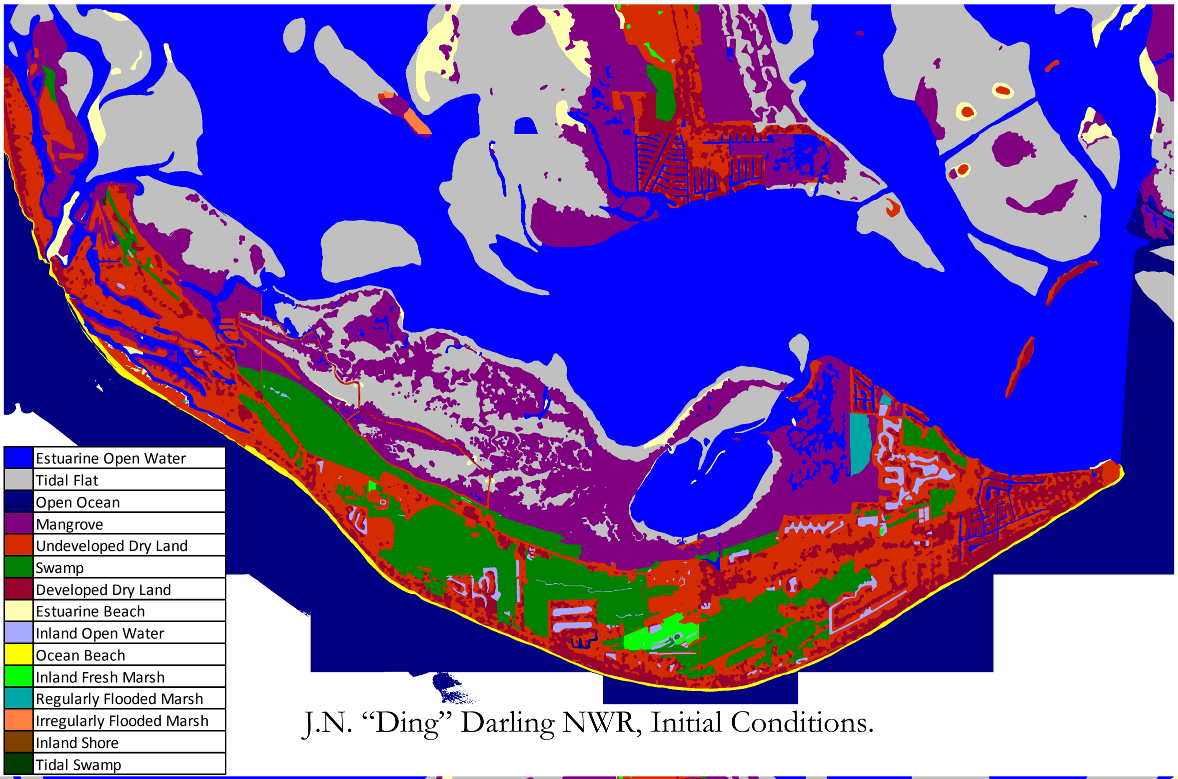

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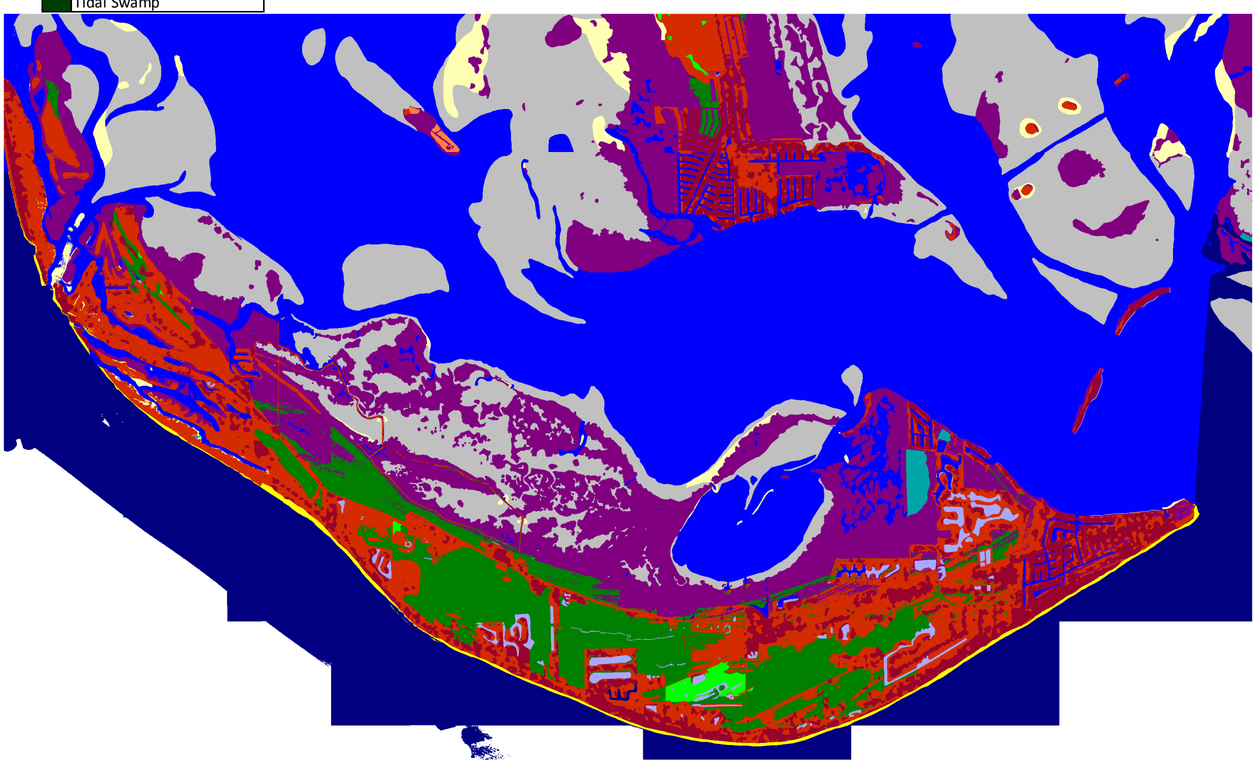
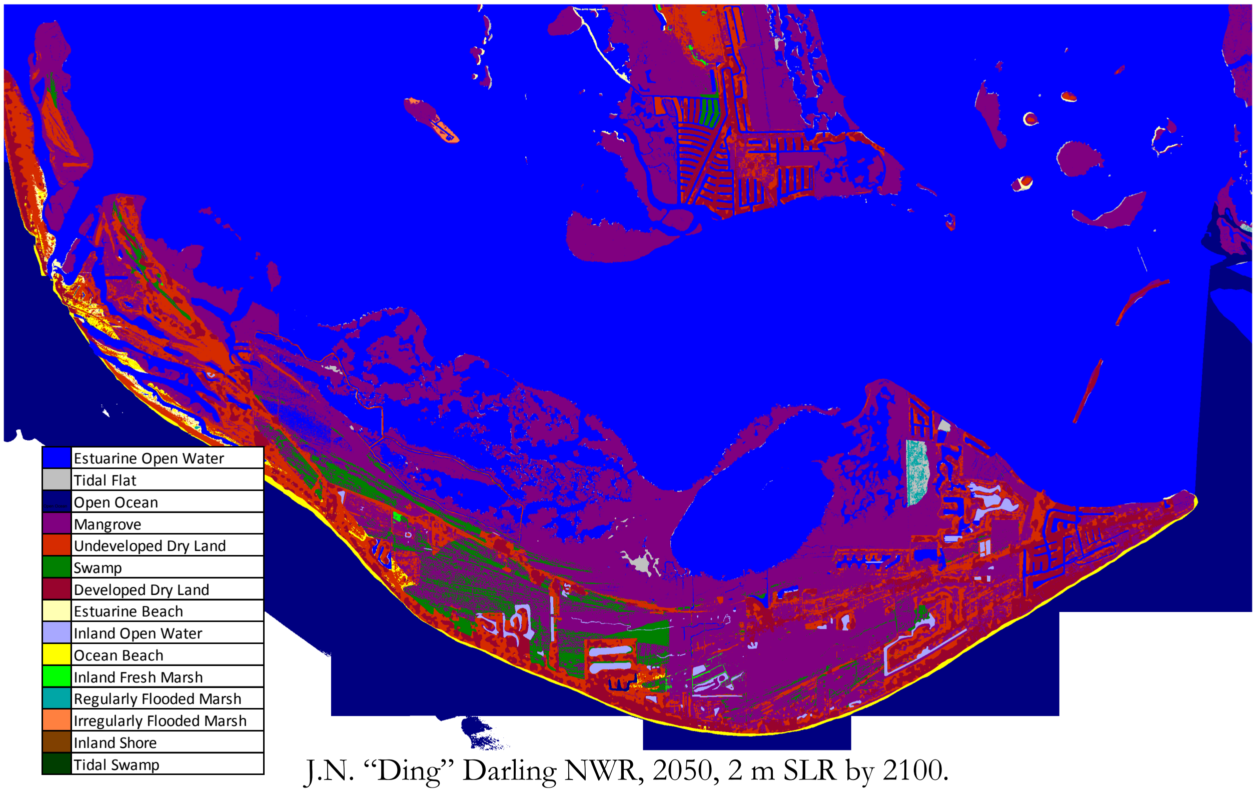


J.N. "Ding" Darling NWR, 2025, 2 m SLR by 2100.



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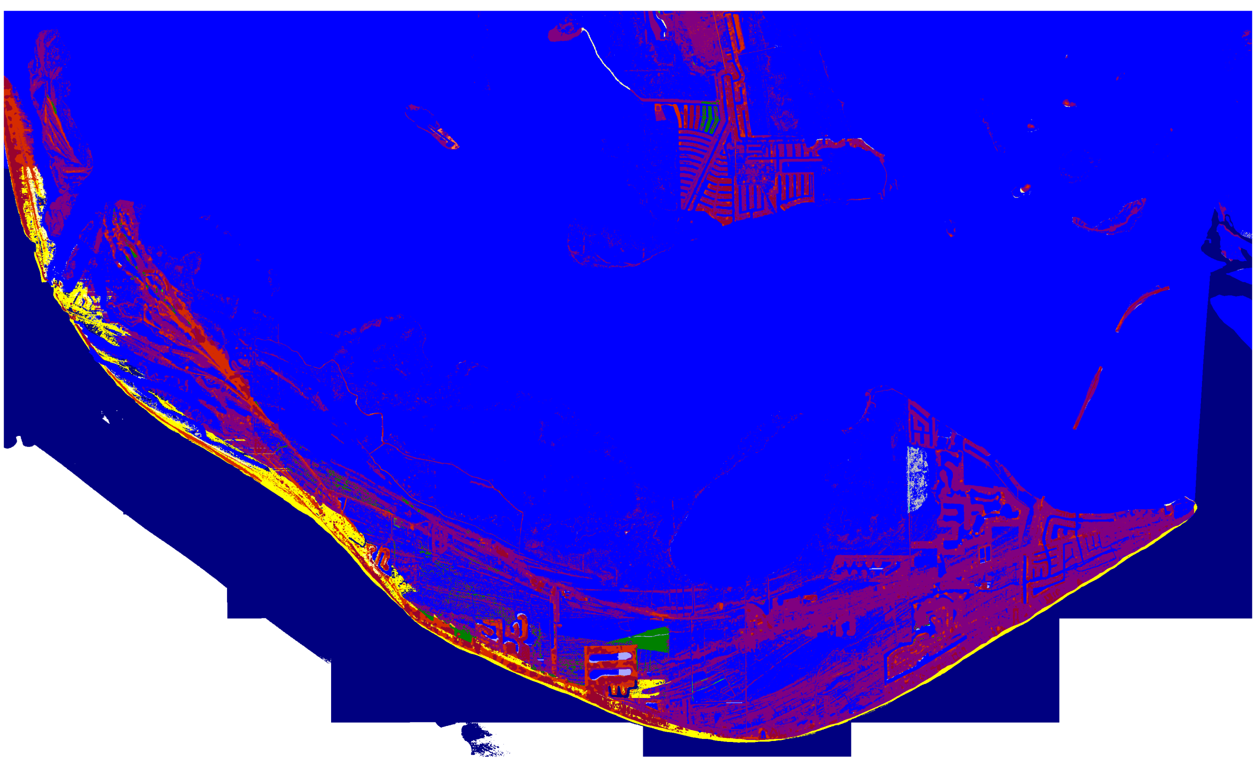
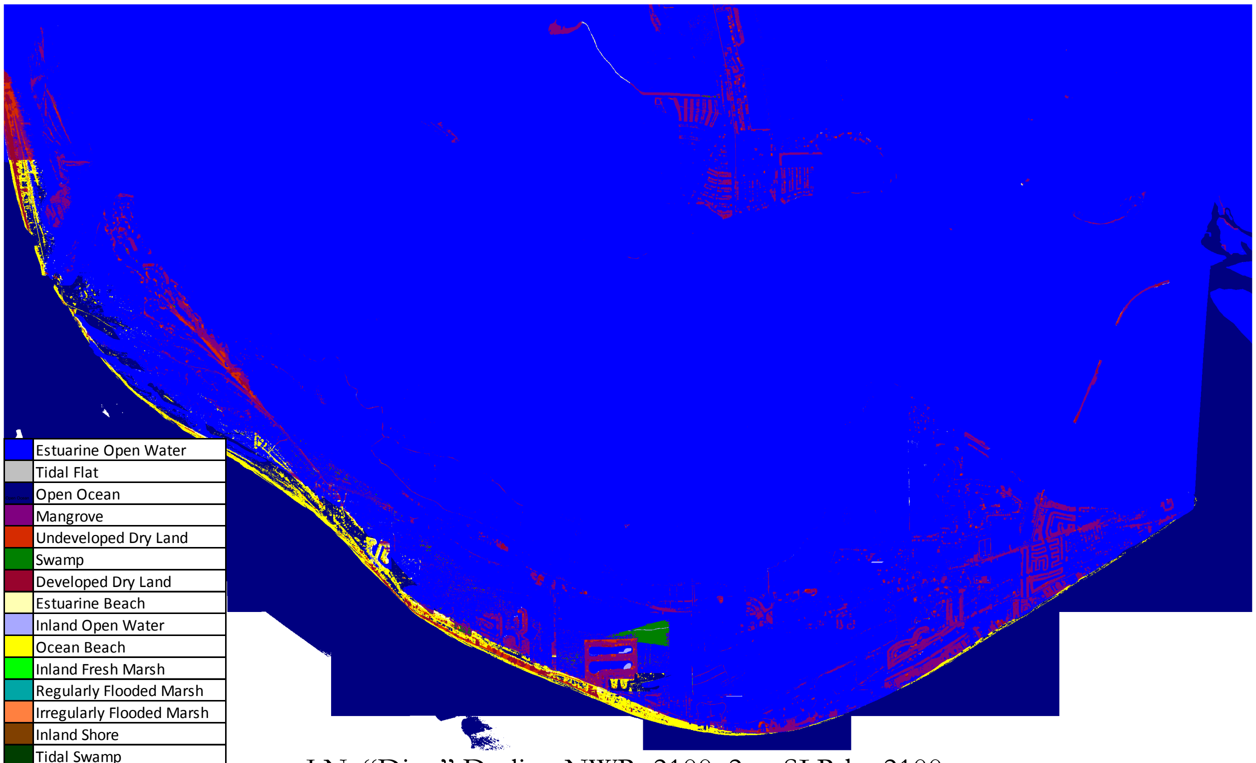


J.N. "Ding" Darling NWR, 2075, 2 m SLR by 2100.



J.N. “Ding” Darling NWR, 2100, 2 m SLR by 2100.