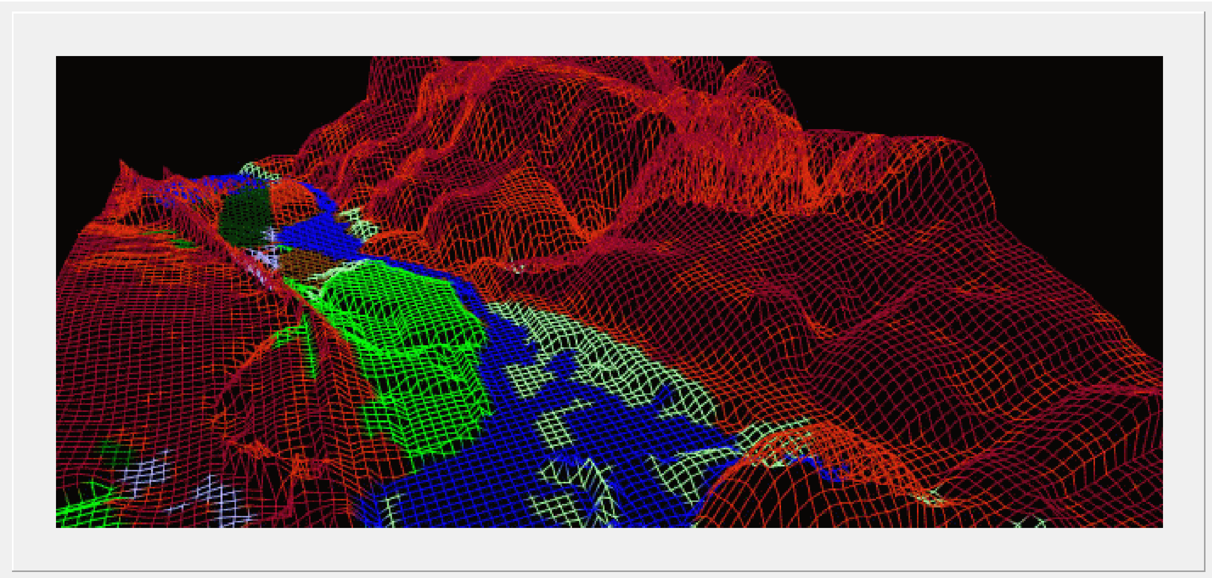
pySLAMM 6.7 Technical Documentation



Sea Level Affecting Marshes Model, Version 6.7 beta

July 2024

warren pinnacle consulting, inc.

pySLAMM 6.7 Technical Documentation

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Acknowledgements

pySLAMM 6.7 is a translation of the SLAMM 6.7 code from Delphi (object-oriented Pascal in Windows) to Python. This project was funded by the Coastal Resilience branch of NCCOS (NOAA) under contract to Consolidated Safety Services Incorporated (CSS) with oversight from Christine Addison Buckel, Ramin Familkhalili and Rebecca Atkins.

All model process code was translated to Python and tested under multiple operating systems. However, the graphical user interface (GUI) is not included. On the other hand, pySLAMM 6.7 can read SLAMM txt files produced by SLAMM 6.7 Delphi and has been tested to machine accuracy against model results produced by SLAMM 6.7 Delphi. In this manner, models can still be produced using the Windows GUI and then production can be completed in python. pySLAMM6.7 can also read inputs from and write outputs to GeoTiff format which simplifies access to model data via GIS.

The SLAMM model can be accessed in Python in several different methods:

- The model can be executed calling a Python script from the command line (SLAMM_Run.py) and passing the model input file as a parameter. A model run will automatically complete.
- A simplified command-line input may be utilized by running the pySLAMM6_7.py file. A set of commands will be shown (e.g. “Load” “Run_model”) if the user enters “?”
- A Python script can be produced that imports SLAMM6.7 objects and modifies those directly in a user-produced script.

This model was developed using Python 3.11. A User’s Manual for pySLAMM6.7 is available to guide users through model installation and the three options for model access discussed above.

As the technical details have not changed between models, and this is primarily a code translation, very little modification to the SLAMM 6.7 technical documentation from July 2016 has been required.

The SLAMM Technical Documentation has been authored by Jonathan Clough of Warren Pinnacle Consulting, Inc. along with Richard A. Park of Eco Modeling, Marco Propato and Amy Polaczyk of Warren Pinnacle Consulting, Inc., Matt Brennan, Dane Behrens, and Bob Battalio of ESA, and Roger Fuller of The Nature Conservancy.

The original Release 6.7 of SLAMM included many California-specific updates, a significant upgrade to the marsh-erosion component, and the capability to track carbon sequestration budgets. The model code is a significant step closer to allowing landscape categories to be flexible and editable within its interface. This work has been funded by The Nature Conservancy under the guidance of Walter Heady. Critical partners in terms of creating this version and the science behind it were ESA, and particularly Matt Brennan and Bob Battalio.

Release 6.6 of SLAMM added the potential for linkage to multiple types of input from spatial salinity models, a submerged-aquatic vegetation (SAV) module, and several interface upgrades as funded by USGS under the guidance of Debbie Reusser.

The 64-bit version of SLAMM contained in Release 6.2 and consequent updates to the technical documentation were funded by the United States Fish and Wildlife Service under the guidance of Dr. Brian Czech.

The uncertainty-analysis component was funded by Ducks Unlimited Inc., under the guidance of Tom Dwyer.The sensitivity-analysis component was added while developing analyses with The Nature Conservancy through a grant from the Gulf of Mexico Foundation to support the Habitat Conservation & Restoration Team, a part of the Governor's Gulf of Mexico Alliance.

Many thanks to Bill Wilen of the National Wetlands Inventory (NWI) who carefully examined all of the NWI to SLAMM code linkages and provided important feedback that appears within this document. Bill also examined the "California Crosswalk" provided in Appendix A.

The upgrades resulting in SLAMM version 6.0 were funded through a grant administered by (and with the assistance of) The Nature Conservancy.

The command line addition was funded by the University of Florida with special thanks to Dr. Rafael Munoz-Carpena. Additional output refinements were funded by Industrial Economics under contract to the US Environmental Protection Agency. An EPA STAR grant was instrumental in creating SLAMM 5.0 along with the guidance of Dr. Christopher Craft of Indiana University and Dr. Jeff Ehman of Image Matters.

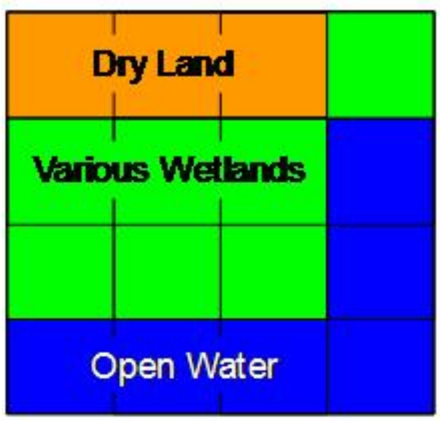
Jim Titus of U.S. EPA helped form the conceptual model at the heart of SLAMM with his significant forward-looking vision during the mid 1980s.

The SLAMM model would not exist were it not for the efforts of Dr. Richard A. Park who was instrumental in the creation of versions one through five and provided many hours of uncompensated feedback after his retirement.

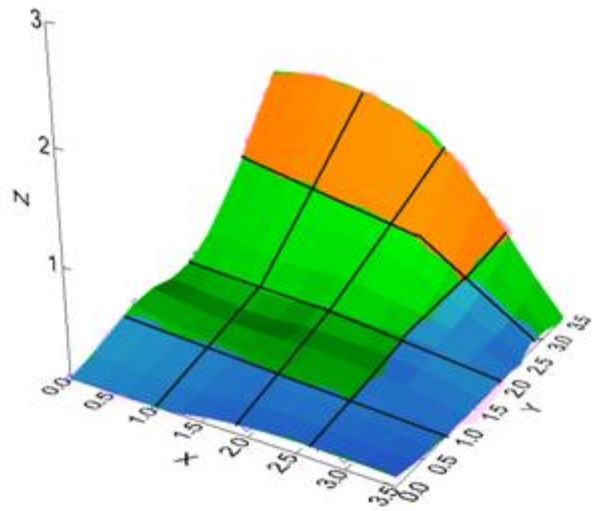
Introduction and Summary

The Sea Level Affecting Marshes Model (SLAMM) simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea level rise. Tidal marshes can be among the most susceptible ecosystems to climate change, especially accelerated sea level rise (SLR).

A flexible and complex decision tree incorporating geometric and qualitative relationships is used to represent transfers among coastal classes. Each site is divided into cells of equal area, and each land-cover class within a cell is simulated separately. SLAMM is flexible with regards to cell-size; cell widths usually range from 5 meters to 30 meters depending on the size of the site and input-data availability. Map distributions of wetlands are predicted under conditions of accelerated sea level rise, and results are summarized in tabular and graphical form.



2D Representation



3D Representation

SLAMM was developed with EPA funding in the mid 1980s (Park et al. 1986), and SLAMM2 was used to simulate 20% of the coast of the contiguous United States for the EPA Report to Congress on the potential effects of global climate change (Park et al. 1989a, Park et al. 1989b, Park 1991a, Titus et al. 1991); the results were quoted by President Clinton ten years later. Subsequently, more detailed studies were undertaken with SLAMM3, including simulations of St. Mary's Estuary, FL-GA (Lee et al. 1991, Lee et al. 1992, Park et al. 1991b), Puget Sound (Park et al. 1993), and South Florida (Park and Lee 1993). SLAMM4 was applied to all of San Francisco Bay, Humboldt Bay, and large areas of Delaware Bay and Galveston Bay (Galbraith et al. 2002, Galbraith et al. 2003). SLAMM4.1 was applied to nine sites in Florida (NWF, 2006). SLAMM 5 was developed as part of an EPA STAR grant and was applied to South Carolina and Georgia as part of that project (Craft et al., 2009). SLAMM 6 represents a significant step forward with regards to the graphical model interface, as well as other added capabilities and model flexibility as described in the next sections.

What's New in SLAMM 6.7

SLAMM 6.7 includes two alternative models for modeling habitat succession under sea-level rise. First, the "traditional" SLAMM Categories from SLAMM 6.6 and previous are maintained within the model. Secondly, a new set of categories specific to California estuaries have been developed along with an updated "decision tree" as described at the end of this document. A conceptual model of California estuaries' response to sea level rise was developed that serves as the framework for representing these estuaries within SLAMM.

Other updates to SLAMM 6.7 include

- **Editable sea-level rise curves:** *Summary TBA*
- **"Run-record" file:** *Summary TBA*
- **Improved modeling of marsh erosion :** *Summary TBA*
- **Carbon Sequestration:** *Summary TBA*

Additional SLAMM Upgrades

The SLAMM 6 model includes multiple upgrades from previous versions both as a result of feedbacks from scientists working in the field and also experience working with the model. The most important changes are listed here.

- **Accretion Feedback Component**: Feedbacks based on wetland elevation, distance to channel, and salinity may be specified as explained in significant detail later in this document.
- **Salinity Model:** Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, 30-day flood tide, and MTL. Habitat switching may be specified as a function of salinity.
- **Linkage to Salinity Models:**
- **Freshwater Influence:** When the salinity model is not included, an area in the study area can be designated as "freshwater influenced" and it is then subject to an alternative flow-chart.
- **Dike/Levee Model:** It is possible to input the elevation of the dikes layer to more realistically model water flows as function of sea level. For backward compatibility, the previous assumption that areas protected by dikes or levees are inundated only when their elevations are less than 2 m below mean sea level may also be used.
- **Integrated Elevation Analysis:** SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets. It is also possible to visualize elevation distribution histograms under different units (m, HTU) and with respect to different zero elevations (MTL, HLLW, NAVD88, …)
- **Flexible Elevation Ranges** for land categories: If site-specific data indicate that wetland elevations range outside of SLAMM defaults, a different range may be specified within the interface.

- **Improved Memory Management**: SLAMM no longer requires that maps be stored in contiguous memory which considerably improves memory management.
- **OpenGL 3D rendering** of SLAMM landscapes including rendering of tide ranges: This feature is important for understanding spatial relationships and for quality assurance of spatial inputs.
- **File Structure:** SLAMM now saves all model parameters and user choices in new *.SLAMM6 file-structure and includes a "recently-used files" menu. Parameters can also be viewed and edited in a text file format.
- **GUI improvements:** Integration of site and sub-site parameters into a single matrix that may be edited, exported to Excel, or pasted into the GUI from Excel.
- **Integrated Help File / User's Manual:** Available in pdf format and also context-sensitive help in HTML help format.
- **File-Setup Verification:** Ensures input rasters have the correct format and that appropriate files have been specified. File-names and locations now are flexible. User-friendly error messages are displayed if files are not compatible.
- **New Maps**: Screen maps of elevations, salinity, variable accretion rates, subsidence rates, NAVD88 correction map, calculated marsh and beach erosion rates, and simplified categories are available in "Set File Attributes" and "debug-mode" execution as well as automatic pasting of maps to Microsoft Word.
  - GIS Elevation maps may be also output for each time-step output in "meters above MTL" units.)
- **SLAMM Colors:** SLAMM land-cover colors are editable and choices are saved along with parameters in the SLAMM6 file
- **Redesigned Interface:** The interface under "Set Map Attributes" is more logically organized into "Edit Subsites," "Analysis tools," and "Edit Cells" tabs.
  - User can pan through larger maps using the new "pan tool."
- **Improvements to open-source code availability:**
  - Non-distributable third party components have been replaced.
  - Obsolete portions of the code have been removed.
- **Command-Line Support:** If parameters are saved in a text file, an "Execute Immediately" option is present which allows for DOS batch-file manipulation or manipulation with independent sensitivity and uncertainty analysis software.
- **Linkage to multiple types of input from spatial salinity models**
- **Submerged-aquatic vegetation (SAV) module**
- **64-bit implementation:** As of SLAMM 6.2, a native 64-bit version of SLAMM has been available for each model release. With 64-bit software, the execution of SLAMM is limited only by the available memory of the user's computer.
- **Overwash Removed:** The relatively-simple barrier-island-overwash component of SLAMM was removed in this version as it is not appropriate to use in simulations of less than 30-meter cell size (which now represent the majority of SLAMM simulations). If funding is available, a more sophisticated overwash component can be added in for future editions, refining some of the formulations from the now obsolete submodel. A user that wishes to use the Overwash component can run SLAMM 6.6 or earlier versions.

Model Execution

Within the SLAMM model, relative sea-level change is computed for each cell in each time step; it is the sum of the historic eustatic trend, the site-specific or cell-specific rate of change of elevation due to subsidence and isostatic adjustment, and the accelerated rise depending on the scenario chosen (Titus et al. 1991, IPCC, 2001). A spatial map of land uplift or subsidence may be specified.

Sea level rise is offset by sedimentation and accretion. There are three options for specifying accretion rates within the model:

- Use average or site-specific values for each wetland category.
- Use spatially varying values for each wetland category.
- Specify accretion as a time-varying function of cell elevation, wetland type, salinity, and distance to channel.

For each time step the fractional conversion from one class to another is computed on the basis of the relative change in elevation divided by the elevation range of the class in that cell. For that reason, marshes that extend across wide tidal ranges are only slowly converted to tidal flats. Assumed wetland elevation ranges may be estimated as a function of tidal ranges or may be entered by the user (as a function of tidal ranges or elevation in meters) if site-specific data are available. When high-vertical-resolution elevation data are available, the model will provide detailed statistics and histograms that clarify the current elevation ranges of wetlands as a function of tidal range.

In the traditional model, if a cell is defined as protected by a dike or levee it is not permitted to change. The existence of these dikes can severely affect the ability of wetlands to migrate onto adjacent shorelines. Diked wetlands are assumed to be subject to inundation when relative sea-level change is greater than 2 m, although that assumption can be changed. In SLAMM 6.7 it is also possible to enter the elevation of the levees or dikes on a cell by cell basis or to use a connectivity algorithm along with cell elevations to determine when a dike is overtopped.

In addition to the effects of inundation represented by the simple geometric model described above, second-order effects occur due to changes in the spatial relationships among the coastal elements. In particular, the model computes exposure to wave action in two ways. In the simplest model if the fetch (the distance across which wind-driven waves can be formed) is greater than 9 km, the model assumes erosion will occur at a user-specified rate. In SLAMM 6.7, marsh erosion can be calculated as a proportional to calculated wave power which is a function of dominant wind directions, observed wind speeds, wave fetch, and water depths. Ocean-beach erosion can optionally be modeled using a relationship reported by Bruun whereby recession is 100 times the change in sea level (Bruun, 1962).

Erosion of dry lands is ignored; in the absence of site-specific information, this could underestimate the availability of sediment to replenish wetlands where accelerated bluff erosion could be expected to occur. Coastal swamps and fresh marshes migrate onto adjacent uplands as a response of the water table to rising sea level close to the coast; in future versions this could be modified to take advantage of more site-specific predictions of water table elevations.

When abundant freshwater is present, wetlands often overlap in elevation ranges and may be better specified as a function of water salinity (e.g. tidal swamp, tidal fresh marshes, and irregularly flooded (brackish) marshes. A fairly simple salt-wedge salinity model is included within this model and rules may be specified to convert wetland types on the basis of salinity.

Sea Level Rise Scenarios

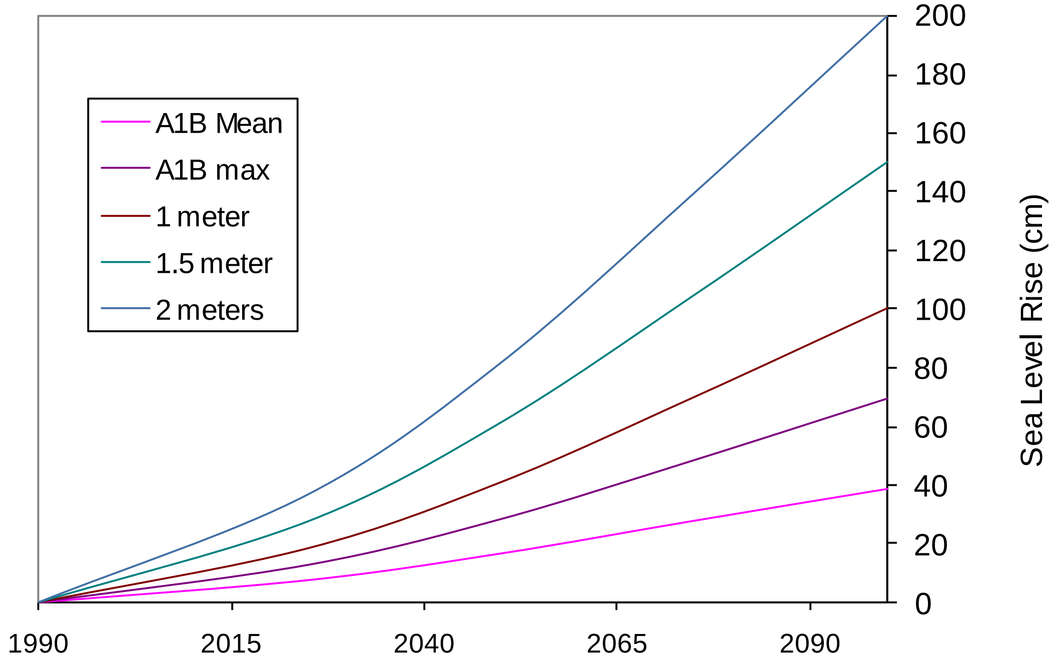
SLAMM has traditionally been run using a set of sea level rise scenarios was taken from the Intergovernmental Panel on Climate Change (IPCC 2001). Current literature indicates that the eustatic rise in sea levels is progressing more rapidly than was previously assumed, perhaps due to the dynamic changes in ice flow omitted within the IPCC report's calculations (Chen et al., 2006, Monaghan et al., 2006, Rahmstorf et al., 2012). Rahmstorf (2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. This work was updated and ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). A 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 sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) Grinsted et. al. state that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits" (2009). Pfeffer et al. (2008) suggests that 2 meters by 2100 is at the upper end of plausible scenarios due to physical limitations on glaciological conditions.

To allow for flexibility when interpreting model results, additional sea level rise scenarios are included that allow the user to model 1 meter, 1½ meters, and 2 meters of eustatic sea level rise by the year 2100, or a custom SLR as discussed below. The A1B- maximum scenario was scaled up to produce these bounding scenarios (Figure 3). In this manner, the relative rate of sea level rise is the same between the A1B scenario and the 1, 1½ and 2 meter scenarios but the extent of sea level rise by the year 2100 is allowed to vary.

New to SLAMM 6, a user can specify any SLR by 2100 in meters. SLAMM will scale the A1B scenario to estimate time-varying Sea Level Rise that will result in the specified degree of eustatic SLR by 2100.

In SLAMM 6.7, a user may also enter any time-series of SLR that would be appropriate for their project, with a base year specified and then a matrix of data (with years in one column and SLR in the second column in units of "meters above the base year"). If a modeled year falls between two years, the model will estimate the SLR through linear interpolation. The model must not be run beyond the last year of the time-series specified (SLAMM will not extrapolate). Included with the SLAMM6 installation files are a set of SLR scenarios taken from NRC 2012 that can be directly loaded into the custom-SLR interface.

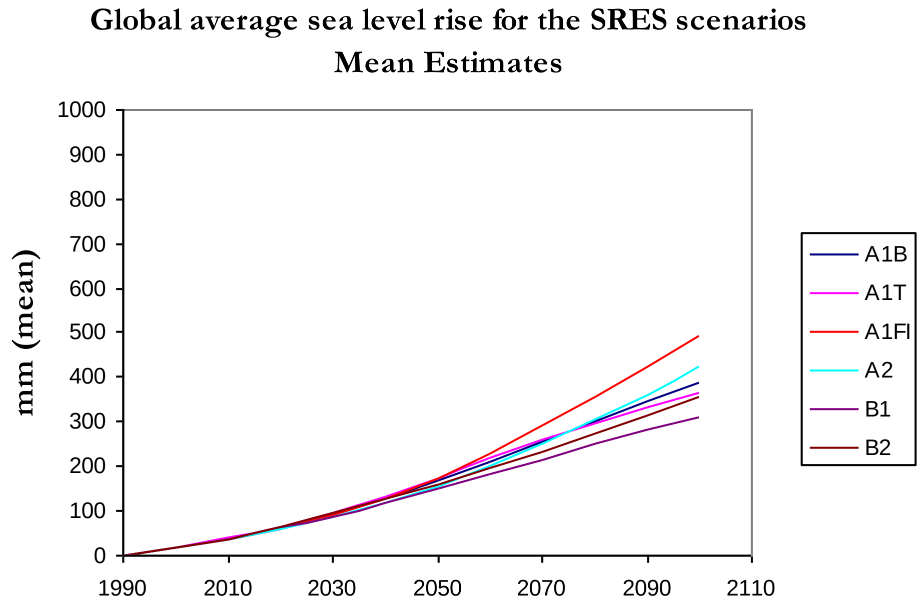
Figure 1: Scaling from IPCC scenario A1B to the 1, 1½ and 2 Meter Scenarios

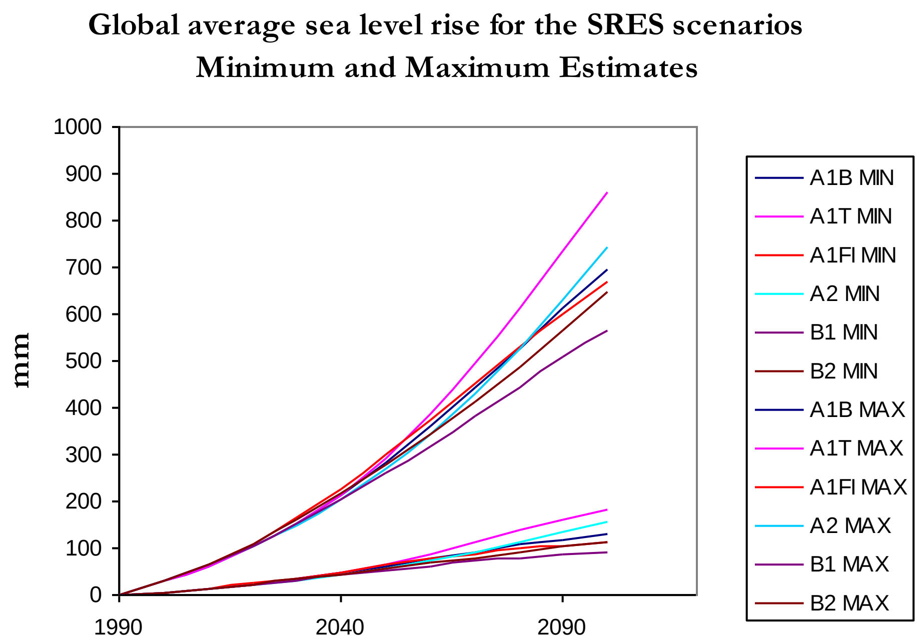


Additionally, IPCC 2001 scenarios remain programmed into the model. The relevant scenarios are briefly described below (IPCC, 2001, Box 5):

> A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

Figure 2: Summary of SRES Scenarios





A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels."

Table 1: SLAMM INPUTS BASED ON IPCC, 2001 (Eustatic Sea Level Rise in mm)

Min

	A1B	A1T	A1FI	A2	B1	B2
2025	28	27.5	30	26	27	28.5
2050	63	66	64	58	52	56
2075	100	125	94	103	76	85
2100	129	182	111	155	92	114

Mean

	A1B	A1T	A1FI	A2	B1	B2
2025	76	81.5	75.5	74.5	75.5	79
2050	167	175	172	157	150	160
2075	278.5	278	323	277	232.5	255
2100	387	367	491	424	310	358

Max

	A1B	A1T	A1FI	A2	B1	B2
2025	128	128.5	137	126.5	128	134
2050	284	291	299	269	259	277
2075	484.5	553	491	478	412.5	451
2100	694	859	671	743	567	646

Source: http://www.ipcc.ch/ipccreports/tar/wg1/553.htm

Elevation Data Inputs

Digital Elevation Maps

High vertical-resolution elevation data may be the most important SLAMM data requirement. Elevation data demarcate where salt water is predicted to penetrate and, when combined with tidal data, the frequency of inundation for wetlands and marshes. Elevation data also help determine the lower elevation range for beaches, wetlands, and tidal flats—the elevation at which point they are inundated too frequently and are predicted to convert to a different type of land-cover or open water.

Whenever possible, bare-earth LiDAR should be utilized to run the SLAMM model as this reduces model uncertainty considerably (Gesch, 2009). Some LiDAR data is available from the National Elevation Dataset (NED) and the Digital Coast database of the NOAA Coastal Services Center also contains a large repository of LiDAR data sets.

Elevation data must be corrected so that mean tide level is set to zero (which is the internal SLAMM datum). The required NED data adjustment is as follows:

$$Elev_{MTL=0} = \left(Elev_{NAVD88=0} - NAVDcorr\right) \qquad \textbf{(1)}$$

where:

Elev$_{Datum}$	=	Elevation of each cell given relevant datum (m);
NAVDcorr	=	Site, sub-site, or cell-by-cell correction, MTL minus NAVD88 (m).

The NAVDcorr or "MTL-NAVD88" in the interface may be derived by determining the MTL elevation (relative to some vertical datum) minus the NAVD88 elevation (relative to that same vertical datum).

In other words, if you have a NOAA gage such as
http://tidesandcurrents.noaa.gov/data_menu.shtml?unit=0&format=Apply+Change&stn=8452660+Newport,+RI&type=Datums

And you see the following lines:

```
MTL       1.148     Mean Tide Level
NAVD      1.199     North American Vertical Datum
```

In this case, the parameter would be 1.148 - 1.199 or **negative** 0.051 (-0.051).

The NOAA VDATUM product is often the best source of vertical datum corrections and provides spatially variable corrections for most of the coastal contiguous United States. SLAMM can now accept spatial maps of vertical datum corrections that can be derived from VDATUM. To get the correct sign (+-) that SLAMM expects using VDATUM, convert from MTL to NAVD in units of meters.

If elevation data are delivered in a non-NAVD88 datum a conversion to a dataset with a vertical datum of MTL must still be completed. The model does not require NAVD88 data specifically, just that data be converted to an MTL basis. The user can either convert to a MTL basis prior to importing the data to SLAMM and set the "MTL-NAVD88" correction to zero, or use the other datum and interpret the "MTL-NAVD88" parameter to mean "MTL minus other datum."

There is a temporal aspect to the conversion of the Digital Elevation Map (DEM) datum as well. Quite often the DEM photo date and the wetland coverage layer photo date differ. Therefore, SLAMM processes elevation data prior to imposing SLR scenarios in order to convert the DEM photo date to the wetland layer photo date. The basic steps of this DEM date conversion are as follows:

- Start with a DEM (with date x) with an NAVD88 datum
- Convert the DEM from date x to the NWI photo date by trying to account for land movement (isostatic rebound or subsidence). *This estimate of local land movement is derived from the difference between local SLR and eustatic SLR, or alternatively a spatially explicit land-movement map.*
- Convert the DEM (now with NWI photo date) to an MTL datum (current tidal epoch) from the NAVD88 datum using NOAA VDATUM results or gage data.
- The result is a DEM relevant to the NWI photo date with an MTL basis (current tidal epoch).

SLAMM assumes that the most recent tidal epoch is relevant to the NWI photo date. This is usually the case except for much older NWI data for which an MTL to NAVD88 correction from an older epoch may be utilized, (if available).

NWI Preprocessor

SLAMM was designed prior to the advent of LiDAR data, so it can model areas with lower-quality elevation data. It is strongly recommended, however, that LiDAR data be used to provide significantly more accuracy to model results.

If using older (highly-uncertain) elevation data the model estimates coastal-wetland elevation ranges as a function of tide ranges and known relationships between wetland types and tide ranges. However, this tool assumes that wetland elevations are uniformly distributed over their feasible vertical elevation ranges or "tidal frames"—an assumption that may not reflect reality. If wetlands elevations are actually clustered high in the tidal frame they would be less vulnerable to SLR. If wetland elevations are towards the bottom, they would be more vulnerable. LiDAR data for any site assists in reducing model uncertainty by characterizing where these marshes exist in their expected range. Additionally high vertical-resolution data can be used to validate model assumptions regarding the elevation range to tide range relationship for these wetland types.

SLAMM processes wetlands elevations unidirectionally away from open water. The front edge of each wetland type is assigned a minimum elevation, specific to the wetland category that it falls into. The back edge of each wetland type is given the maximum elevation for that category. The slope and elevations of the intermediate cells are interpolated between these two points.

The minimum and maximum wetland elevations also vary depending on site characteristics. The default model assumptions regarding wetland elevation ranges are shown below but these can be edited by the user on a site-by-site basis.

Table 2: Default Minimum and Maximum Elevations Assumed by the SLAMM Model
(Note, these ranges are fully editable within SLAMM 6)

Wetland Type:	Minimum Elevation:	Maximum Elevation:
Reg. Flooded Marsh	Mean Tide Level	120% of MHHW
Estuarine Beach	Mean Lower Low Water	Salt Boundary
Ocean Beach	Mean Lower Low Water	Salt Boundary
Trans. Salt Marsh	Mean Higher High Water	Salt Boundary
Irreg. Flooded Marsh	Average(MHHW, MTL)	Salt Boundary
Ocean Flat	Mean Lower Low Water	Mean Tide Level
Mangrove	Mean Tide Level	Salt Boundary
Tidal Flat	Mean Lower Low Water	Mean Tide Level
Rocky Intertidal	Mean Lower Low Water	Salt Boundary

To better understand the elevation pre-processor, it is useful to look at a specific example. Take the case of a site in which open water lies to the south of the land. The pre-processor will assign elevations along horizontal strips of cells moving from west to east. Each strip will be processed from south to north, assigning increasing elevations to each wetland category encountered. However, this algorithm will occasionally create significant ledges in elevation moving horizontally over a given wetland. In order to avoid these ledges, the pre-processor averages the calculated elevation of each cell with the cell adjoining it horizontally that has already been processed. In this case, the cell elevation is averaged with the cell directly to the west. Elevations are averaged only if the adjoining cell is of the same wetland category as the cell being processed.

Finally, if there is water on the upper end of the wetland as opposed to an upland category, the wetland's maximum elevation is set to the average of the wetlands original high and low elevations. In other words, in this case, interpolations occur between the cell's low elevation and half-way between the low and high elevations presented in Table 2 (or custom ranges as input by the user).

If superior elevation data are available for modeled site (i.e. LiDAR data) the elevation preprocessor should be turned off. The flag to turn on and off this processor is one of the site or sub-site parameters. In this manner, a site that is only partially covered by LiDAR data can still be simulated, with only a portion of the map being subject to the pre-processor's estimations.

Elevation Data Quality Assurance

To improve model predictions, it is important to ensure that NED Elevation data and NWI pre-processor data line up properly. Potential for errors include:

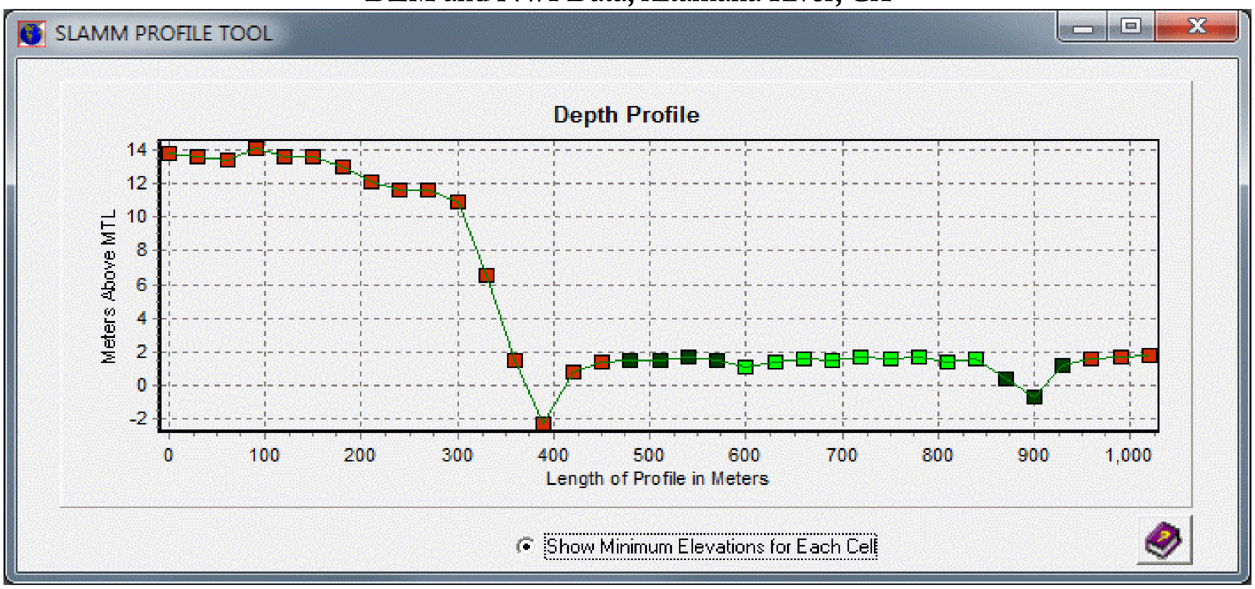
- offsets between NWI and LiDAR dates;
- horizontal errors in NWI data;

- parameterization errors in the NAVD 88 correction **(1)** or tidal ranges;
- variability in the historic trend that is applied to unify the DEM and NWI data **(2)**; or,
- errors due to the accuracy of the DEM or DEM interpolation procedures.

Note: The sections below pertaining to the SLAMM GUI are relevant to the Delphi, Windows version of SLAMM only. However, model inputs from Delphi SLAMM can be saved to txt format and run in pySLAMM 6.7.

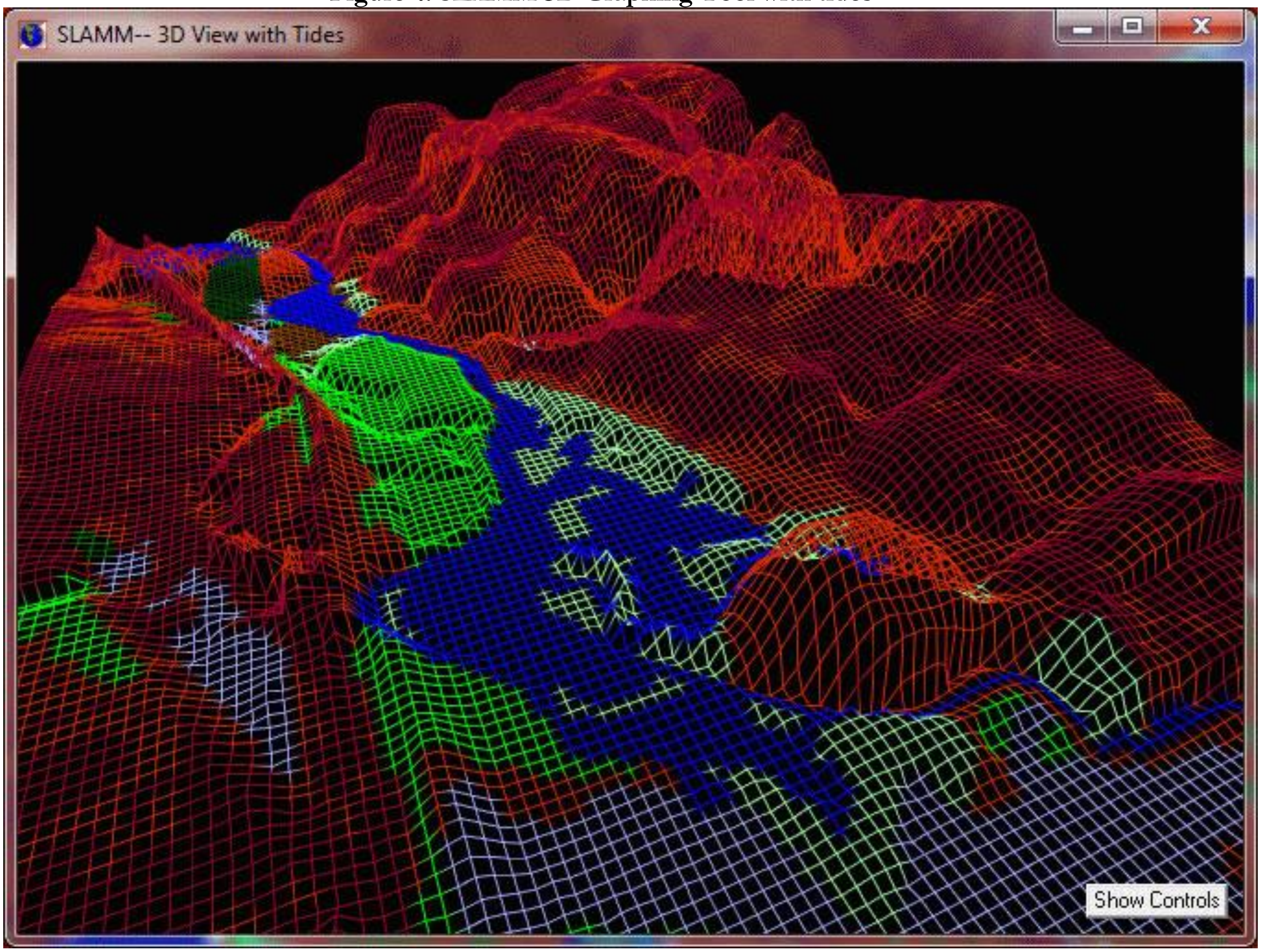
A number of quality assurance tools have been integrated into the SLAMM 6 interface to help assess these potential glitches. For example, an elevation profile tool may be used to graphically represent the elevation profile of any line drawn on the site map.

Figure 3: SLAMM Profile Tool Illustrating the Interface Between DEM and NWI Data, Altamaha River, GA



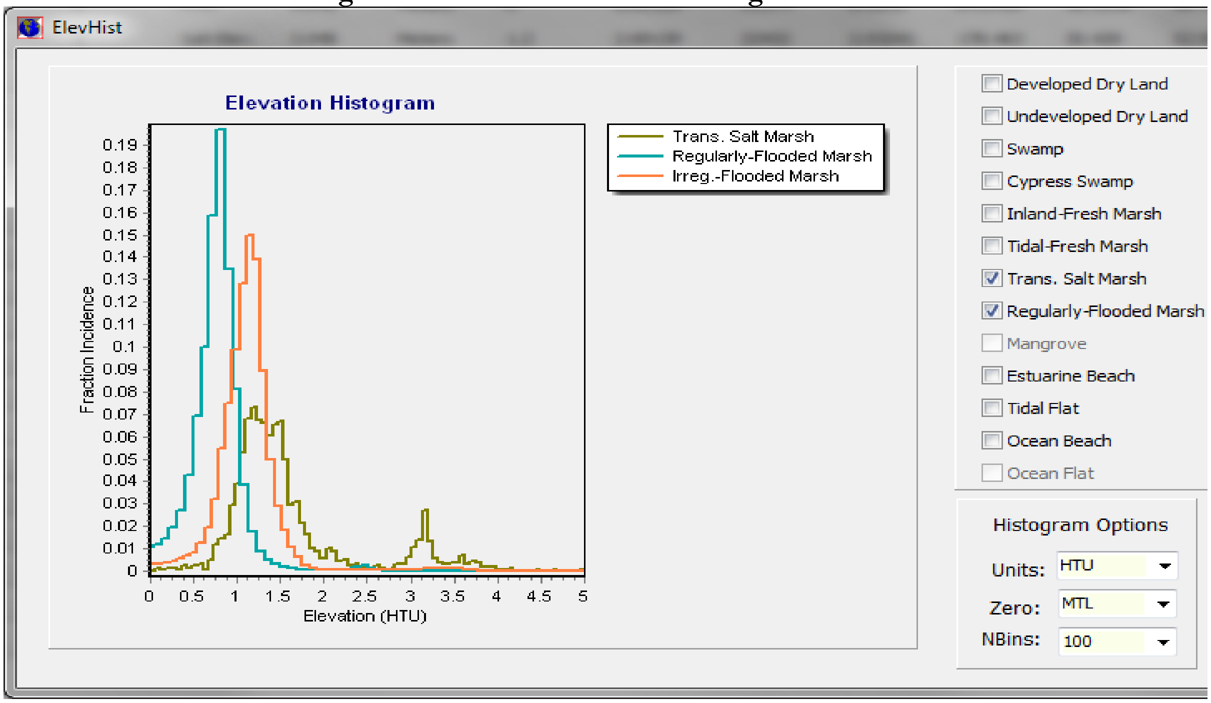
An Open-GL 3D graphing tool has also been added to SLAMM 6 that allows the user to see the three dimensional elevation model that underlies the map of wetlands categories. The user may navigate around this map and change elevation magnification to better understand the nature of their NWI-to-elevation relationship. Water levels at various tides may also be animated on top of the 3D graph. Maps may be generated at each step of a SLAMM simulation as well. This is important as 3D graphing is one of the most important ways to provide quality assurance for DEM maps.

Figure 4: SLAMM 3D Graphing Tool with tides



SLAMM 6.7 provides an additional elevation-analysis tool. It is now possible to visualize the elevation-distribution histogram for each wetland category in different units (meters or "half-tide" units) and with respect to different zero elevations (MTL, MHHW, MLLW and NAVD88). This can help verify the consistency of the conceptual model with respect to available wetlands and elevation data. Histograms may also be exported to Excel for further analysis. Figure 5 shows an example of this elevation-histogram capability.

Figure 5: SLAMM Elevation Histograms Interface



Levee and Dike Data Input

The presence of dikes protecting wetlands and dry lands may be partially determined from NWI data. NWI dike data are often incomplete, though, especially for dikes that protect non-wetland areas. Additional data sources should be utilized to augment the NWI dike coverage such as USGS topographical maps, Army Corps of Engineers layers, and local sources of information.

Levees and dikes are entered as an input raster. Using the "classic" SLAMM dike model this input grid identifies protected cells (non-zero entries represent protected regions; zero or no-data entries otherwise). Not only dike locations, but also lands protected by these dikes must be specified as part of the dikes layer. This model assumes that these areas will not be inundated given RSLR below 2 m. For backward compatibility, this option is maintained.

In SLAMM 6 it is also possible to enter the elevation of the levees or dikes on a cell by cell basis. When levee elevations are provided with respect to NAVD88, SLAMM combines the DEM and levee/dike elevation data to obtain the overall elevation for each cell. In this case, only the levee locations must be specified, rather than identifying areas that are protected or unprotected by levees or dikes. During the simulation, SLAMM searches for water inundation paths using the connectivity algorithm that is checked by default (see *Connectivity* on page 24 for further details).

Finally, it is possible to combine this new levee model with the older SLAMM dike model in a single simulation. This can be useful when using mixed data sources. For example, NWI data are more compatible with the "classic" dike model as they indicate whether a wetland is protected by a levee or a dike but do not include elevation data. To use both models simultaneously, both data types must be combined into a single raster with the number "negative five" (-5) representing regions that should be protected using the "classic" dike model, and any positive number representing dike elevations. When using both models combined, the user should characterize this hybrid raster as "dike location raster" within the file-setup interface.

If future plans for dike removal or dike addition are known, or can be estimated, a time-series of dike rasters may be specified. See the User's Manual for more details on this procedure.

Dry Land Protection

In addition to representing levees and dikes, SLAMM has the capability to represent two land-protection scenarios. Simulation options allow for the optional protection of developed areas or all dry land (developed and undeveloped). Areas so protected are not allowed to convert to other habitat types in the simulations, preventing the capability of wetlands to migrate inland. When dry lands are designated as protected they are not subject to inundation or erosion procedures

Temporal Aspect

The NWI photo date is assumed to comprise the initial conditions for a SLAMM simulation. Depending on the time-step chosen, from this initial condition, the model will first simulate the year 2010, 2020, or 2025 (or a custom year defined by the user). SLAMM will then run using the selected time-step to 2100.

SLAMM can also simulate a "time zero" step, in which the conceptual model can be validated against the data inputs for your site. The time-zero model predicts the changes in the landscape given specified model tide ranges, elevation data, and land-cover data. Any discrepancy in time-zero results can provide a partial sense of the uncertainty of the model. There will almost always be some minor changes predicted at time zero due to horizontal off-sets between the land-cover and elevation data-sets, general data uncertainty, or other local conditions that make a portion of your site not conform perfectly to the conceptual model. However, large discrepancies could reflect an error in model parameterization with regards to tide ranges or dike locations, for example, and should be closely investigated.

When a larger site is run that has several different NWI photo dates, the user may specify which portions of the maps are relevant to which NWI photo dates on a "sub-site" basis. For portions of the map with older NWI photo dates, the inundation and spatial model is run through the latest NWI photo date. A consistent "initial condition" of the model will then be achieved so that the entire map reflects initial conditions (and model predictions) at the most recent NWI photo date.

The NWI photo date and the date of the digital elevation model (NED) may differ. In an attempt to correct any temporal discrepancy in elevations due to land movement, NED data are converted to achieve the same temporal aspect as the NWI data:

$$Elev_{NWI\ Date} = Elev_{DEM\ Date} - \frac{(Year_{NWI\ Date} - Year_{DEM\ Date})(HistoricSLR_{Local} - HistoricSLR_{Global})}{1000} \quad \textbf{(2)}$$

where:

$Elev_{Date}$	=	Elevation at given date (m), *note that as sea levels rise, dry land elevations will fall;*
$Year_{Date}$	=	Year number for given date;
1000	=	(mm/m);
$HistoricSLR_{Local}$	=	Site specific historic trend of sea level rise (mm/yr);
$HistoricSLR_{Global}$	=	Assumed 1.7 mm/yr global historic trend (IPCC 2007).

Elevation Model

Sea level is estimated at each model time step as follows:

$$SLR_{TModel} = GlobalSLR_{TModel} + \frac{(Year_{TModel} - Year_{T0})(HistoricSLR_{Local} - HistoricSLR_{Global})}{1000} \quad \textbf{(3)}$$

where:

SLR_{TModel}	=	Projected local sea level rise at current model year (m);
$GlobalSLR_{TModel}$	=	Global average sea level rise predicted in current model year (m);
$Year_{TModel}$	=	Current model year;
$Year_{T0}$	=	Date when model started (latest NWI photo date);
$HistoricSLR_{Local}$	=	Site specific historic trend of sea level rise (mm/yr);
$HistoricSLR_{Global}$	=	1.7 mm/yr global historic trend from 1900 to 2000;
1000	=	(mm/m).

When projecting future sea-level rise, a question arises as to which portion of the site-specific historic sea-level trend occurred due to global effects. To address this, the global historic trend is subtracted from the local historic trend so that local effects can be estimated. These local effects are then added to global projections of sea level rise to predict the likely sea level at any point in the future **(3)**. The global historic trend is estimated at 1.7 mm/yr based on IPCC 2007 §5.5.2.1 .

Alternatively, if a spatial map of uplift or subsidence is imported into the map, in cm/year, the historic sea level rise parameter becomes irrelevant. Local SLR is estimated by adjusting global sea level rise for local land movement effects:

$$SLR_{TModel} = GlobalSLR_{TModel} - \frac{(Year_{TModel} - Year_{T0})(Uplift_{Cell})}{100} \quad \textbf{(4)}$$

where:

$Uplift_{Cell}$	=	Optional user-input spatial map of land uplift (cm/year);

This equation assumes the differential between global and local sea level rise is exclusively due to land movement, as opposed to other local factors.

Following the lead of IPCC and most other estimation efforts, all global sea-level-rise estimates within the SLAMM model start at the year 1990. If the SLAMM simulation start date (T_0) is not exactly 1990 then model projections must be adjusted to the model start date. If the SLAMM T_0 (the latest NWI photo date) is before 1990 then the local historic trend is added to projected sea level rise:

$$SLR_{TModel} = SLR_{TModel} + \frac{(1990 - Year_{T0})(HistoricSLR_{Local})}{1000} \tag{5}$$

If the SLAMM T_0 is after 1990, any projected sea level rise from 1990 to the model start date is subtracted from projected global sea level rise:

$$SLR_{TModel} = SLR_{TModel} - GlobalSLR_{T0} \tag{6}$$

Relative sea level rise from one time-step to the next can then be calculated:

$$SLRise = SLR_{TCurrent} - SLR_{TPrevious} \tag{7}$$

where:

$SLRise$	=	Sea level rise since previous time step (m);
$SLR_{TCurrent}$	=	Sea level rise projected at current model year (m);
$SLR_{TPrevious}$	=	Sea level rise projected at previous time-step (m).

For each time step, land elevations are adjusted for sea level rise so that MTL remains constant at zero. If sea level is predicted to be rising, land elevations in the model will decrease each time-step while sea level remains constant.

$$MinElev_{Category,t} = MinElev_{Category,t-1} + DeltaT \cdot Accrete_{Category} - SLRise \tag{8}$$

When land is protected by a dike, the accretion or sedimentation is assumed to be zero so the equation becomes:

$$MinElev_{Category,t} = MinElev_{Category,t-1} - SLRise \tag{9}$$

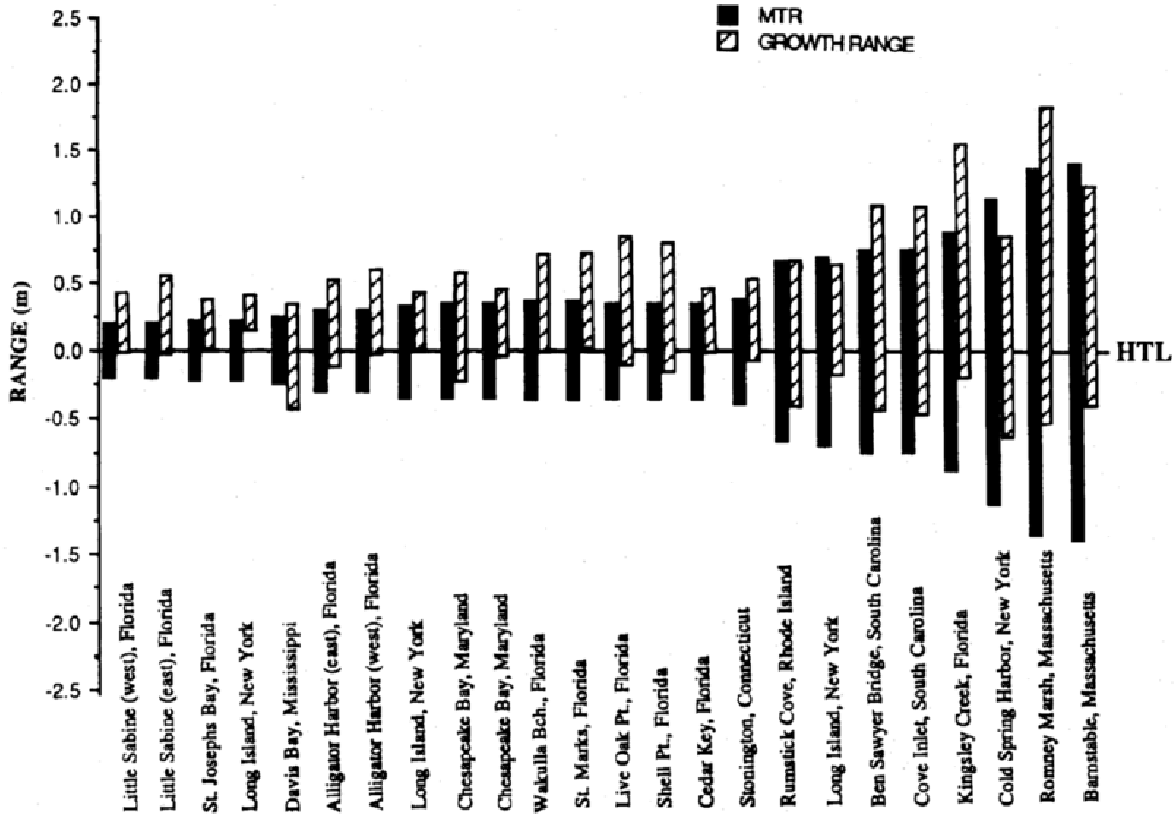
where:

$MinElev_{Category}$	=	Minimum elevation of the relevant category (m);
$DeltaT$	=	Time step (yr);
$Accrete$	=	Accretion or sedimentation rate (m/yr);
$SLRise$	=	Predicted local sea-level rise during time step (m).

Conceptual Model Verification

The SLAMM model assumes that wetlands inhabit a range of vertical elevations that is a function of the tide range. For example, salt marshes are generally assumed to persist from Mean Tide Level (MTL) up to an elevation greater than Mean High Higher Water (MHHW). Based on LiDAR data from many sites, this relationship has been generally proven to be true, though there are occasional site-specific differences. For example, in macrotidal regimes, saltmarshes have been shown to persist several centimeters below Mean Tide Level (McKee and Patrick, 1988).

Figure 6: Elevation ranges of selected Salt Marshes in the US from McKee and Patrick, 1988



Within SLAMM 6, an automatic elevation analysis can be undertaken to examine whether the elevation data and NWI cover class data match the SLAMM conceptual model appropriately. This examination will be most successful when the NWI and LiDAR data have similar dates. Otherwise, statistics will be inaccurate due to changes in land cover classes that may have occurred since the date of the NWI photography. High vertical-resolution elevation data is also required. Additional differences can be expected if the elevation data grid has a higher horizontal resolution than the NWI cover class.

If a site does not match with the current conceptual model particularly well, the SLAMM model may be modified to allow a new elevation-range to wetlands-class relationship (a capability added to SLAMM 6). However, care should be taken to ensure that the reason for the mismatch is not due to some sort of systematic data error (such as a problem with the vertical datum transformation or an inaccurately quantified tidal range). Any changes to the SLAMM conceptual model should be documented along with hypotheses for why the site appears to differ from other sites that have been modeled.

In the case of perched lagoons (such as those occurring throughout California) the elevation-range to habitat relationship is also strongly dependent on estimated or observed lagoonal water levels. See the section on "Representative Water Levels in Lagoon Estuaries" below for more information about how to characterize water levels and understand their relationship to various habitat types.

It should be noted that the SLAMM 5 elevation-range defaults for tidal fresh marsh and tidal swamps suggested that they would be located above the salt boundary with respect to elevation. In the absence of data, we had assumed in our conceptual model that tidal swamp and tidal fresh marshes are fresh-water categories and therefore must be located above the salt boundary with respect to elevation. However, our experience with extensive LiDAR data sets since that time suggests that tidal swamps usually are lower in elevation. For example:

> Grand Bay, MS: "The lowest elevation boundary for tidal swamp was set to 66% of mean higher high water. Based on site-specific data and LiDAR data analyses from other sites, this category often extends below the salt boundary due to the influence of fresh water flows."
>
> Puget Sound: "Another model modification was to reduce the lower elevation range for Tidal Swamp to 0.85 of MHHW. The presence of fresh water flow in tidal swamps allows these tidally influenced swamp lands to exist well below the salt-boundary."

For backwards compatibility to SLAMM 5, the SLAMM 6 lower elevation ranges for these categories remain the "salt boundary." Therefore, the lower boundary for these categories will generally need to be reduced (based on site specific data) or they will potentially convert to another category at "time zero." Due to the importance of fresh water flows for these wetlands, a salinity model should be utilized whenever possible rather than an elevation range model to determine the conversions for these two model categories.

A few notes regarding changing the SLAMM conceptual model follow:

- A user must change the conceptual model with care so that the model being applied does not become illogical.
- For example, minimum elevations for Dry land, Swamp, and Inland-fresh Marsh should not be set below the "salt elevation" to avoid regularly-inundated dry lands or regularly-inundated non-tidal fresh wetlands.
- Similarly, minimum elevations for Dry land, Swamp, and Inland-fresh Marsh elevations should not be set much *above* the "salt elevation" as dry lands would not be predicted to convert to saline wetlands until they are regularly being inundated by water.
- Cypress swamps can handle being semi-permanently flooded, so lowering that elevation boundary may be appropriate.
- For beaches and tidal flats, NWI does not control for tide level when imagery is taken, so sometimes the beach-to-open-water interface can occur closer to MTL. Elevation data may also not be tidally coordinated, increasing uncertainty at this MLLW boundary.
- Elevation ranges for open-water categories are generally unimportant.

- Upper elevations for land-cover categories are not relevant unless the elevation pre-processor is being applied. Aggradation, the creation of beaches or tidal flats or the drying of wetlands when they exceed their upper elevation boundary, is not included in the current implementation of SLAMM 6.

Spatial Model

Overview

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

- **Inundation:** The rise of water levels and the salt boundary is tracked by reducing elevations of each cell as sea levels rise, thus keeping MTL constant at zero. The effects on each cell are calculated based on the minimum elevation and slope of that cell and, optionally, whether that cell is connected to open water.

- **Erosion:** Erosion is triggered based on a threshold of maximum fetch and the proximity of the wetland to estuarine water or open ocean. When these conditions are met, horizontal erosion occurs at a rate based on site specific parameters.

- **Saturation:** Coastal swamps and fresh marshes can migrate onto adjacent uplands as a response of the water table to rising sea level close to the coast.

- **Accretion** Upward movement of marshes due to sequestration of sediments and biogenic production. May be specified on a spatially variable basis or a model of accretion as a function of elevation, salinity, and/or distance to channel may be specified.

- **Salinity:** *Optional.* In a location with defined fresh-water flows, land categories can migrate based on changes in salinity, based on a relatively simple salt wedge model. Variable fresh-water flows may be specified. Alternatively, linked data from existing salinity models may also be specified.

Each of SLAMM's cells may be composed of up to three SLAMM categories. Model initial conditions assign each of these cells to 100% of a single category. However, to allow incremental change in the model in smaller horizontal steps than the cell width, the cell can track the width of multiple classes in a single cell.

Inundation of Wetlands

If the lower boundary of the wetland class has fallen below the minimum elevation, the fraction lost is calculated using the slope.

Calculation of Fraction Lost as a Function of Slope

The fraction of wetland that is lost (transferred to the next class) is calculated as a function of the slope of the cell, the minimum elevation for that wetland, and the lower Elevation boundary for that wetland. The lower Elevation boundary must exceed the minimum elevation for transfer to occur: In that case:

$$FracLost_{Cat} = \frac{\left(\dfrac{LowBound - MinElev_{Cat,t}}{\tan Slope}\right)}{Width_{Cat}} \tag{10}$$

where:

$FracLost_{Cat}$	=	Fraction of wetland in cell lost in time step (unitless);
$LowBound$	=	Elevation lower boundary of wetland class (m);
$MinElev_{Cat,\,t}$	=	Minimum elevation of wetland class in cell at time *t* before conversion (m);
$Slope$	=	Slope of given cell (assumed to be toward water) (degrees).
$Width_{Cat}$	=	Width of the given category in the given cell (m).

This construct assumes that conversion of an area from one class to another is a linear function of the Elevation range that is lost due to sea level rise within the cell.

Aggradation, the creation of land or drying of wetlands when sea levels fall or when accretion rates exceed sea levels, is not included in the current implementation of SLAMM 6.

For marsh categories that are adjacent to water, erosion takes place if the maximum fetch for the given cell is greater than a user specified length (this length was previously hard-wired to 9km; this 9km fetch threshold remains relevant for swamps). Tidal flats are assumed subject to erosion regardless of the extent of wave setup.

$$Additional\ FracLost_{Erosion} = \Delta T \left(\frac{Erosion_{Category}}{Width_{Category}}\right) \tag{11}$$

where:

$Additional\ FracLost_{Erosion}$	=	Additional fraction of category lost due to erosion (unitless);
$Erosion_{Category}$	=	Horizontal erosion of category, input by user (m/yr);
$Width_{Category}$	=	Width of category in current cell (m/yr)’

If sea level rise exceeds sedimentation or accretion and if the minimum elevation of a cell is below the minimum elevation for the relevant wetland category then inundation takes place. Fraction lost is calculated as a function of slope.

Elevation ranges for many wetland classes may overlap. In this case, if further disambiguation is required, the salinity model may be utilized to convert classes.

Connectivity

SLAMM has long assumed that salt water will inundate any non-diked dry lands or fresh water wetlands that fall below the "salt boundary." For the most part this has been an effective assumption (i.e. our "time-zero" or "current condition" model results have never indicated that there are natural ridges protecting low-lying dry land or freshwater wetlands from saline inundation).

However, a few recent sites have challenged this assumption and therefore we have implemented an optional connectivity sub-model within SLAMM 6 following the methods documented in the Poulter and Halpin (2007).

One of the assumptions that was followed from Poulter and Halpin (2007). "We also assumed that the vadose zone (unsaturated soil) and surface roughness did not affect inundation because the time (t) for diffusion was infinity (i.e. the process of sea-level rise overwhelms diffusivity constraints)." This matches well with SLAMM's large-time-step configuration and the attempt to calculate what will happen "at equilibrium" when the sea level rises by a certain extent. (In other words, SLAMM is not a hydrodynamic model.)

The mechanism of this algorithm is that at the beginning of each time-step, each cell is marked with one of the five categories listed below. These categories may be mapped at the beginning of each time-step (when run in debug mode) by selecting the "connectivity" check-box within the model's interface.

- Above Salt Bound – Connectivity is irrelevant [dark green on connectivity map]
- Connected to Salt Water Source [yellow on connectivity map]
- Not Connected to Salt Water Source [orange on connectivity map]
- Irrelevant Land Type (not a dry land or freshwater wetland) [brown on connectivity map]
- Blank or Diked [transparent on connectivity map]

When this model is utilized, if freshwater wetlands and dry lands are not connected to a salt water source, they are therefore not assumed to be subject to saline inundation. An eight-sided connectivity algorithm is utilized to examine whether a cell is connected to an adjoining cell.

If dike features are adequately represented in the digital elevation map (DEM), this model can also be used to assess when a dike will be overtopped, (so long as the area behind the dike is not designated as "diked" in which case it will be assumed to be protected from saline inundation). LiDAR covering bridges will often suggest that there is no connectivity so care must be taken in this case (a DEM adjustment may be warranted to allow connectivity). Alternatively, tide gates are often too small to show up in a DEM; in this case connectivity may be incorrectly assumed over such features.

Also note that this model is sensitive to cell-size as documented in Poulter and Halpin (2007). Generally, larger cell sizes tend to produce more connectivity within a DEM.

Inundation for a test elevation. The algorithm has been recently generalized to calculate water connectivity for different reference elevations. The procedure followed is similar as described above with the only different that the salt bound elevation is substituted by a user defined elevation. In this way inundated areas can be calculated for any water height.

Erosion

Depending on data availability, the purposes of a given study, and the habitat being studied, there are three possible erosion models to choose between. "Wave-action" erosion estimates marsh erosion as proportional to wave power calculated for each cell. These calculations require wind-rose inputs and observed or estimated bathymetry and should be calibrated with observed erosion data when this is available. A simpler model that only considers wave fetch may be appropriate for simpler applications or applications where wind or bathymetry data are not immediately available. Another option is to model ocean-beach erosion using the Bruun rule. More information on these three approaches follows.

Wave-action Erosion

For marsh erosion, the SLAMM model can now include a sophisticated wave-power estimation for each cell rather than exclusively relying on a maximum-fetch threshold to trigger horizontal erosion.

Based on the approach suggested by Marani and coworkers (2011), marsh lateral erosion is estimated based on the total wave power predicted at each marsh-edge cell. The total wave power is a function of average wind speeds and wind-direction data for the site, open-water fetch, and water depths at different tide stages. The Marani paper found that volumetric erosion and linear rates of margin retreat can be assumed to be proportional to the "mean annual wave-power density." The proportionality constant "alpha," that relates wave power to erosion rates, can be calibrated to site-specific data on marsh retreat when these are available.

The precise steps taken in the calculation of wind-erosion, and the equations that govern these calculations are presented below.

For each marsh-to-open-water or marsh-to-tidal flat cell the model will take the following steps:

1. Iterate through 16 directions from wind rose data entry.
2. Iterate through wind speeds from 7 entry columns in wind rose (m/s).
3. Iterate through five tidal levels. (The model currently calculates wave powers at MLLW, MTL, MHHW, and the midpoints between MLLW and MTL, and MTL and MHHW.)
4. Calculate the fetch along the selected wind direction.

5. If the fetch is greater than zero then calculate average water depth along the fetch
   a. If bathymetry data are available then calculate the weighted-average depth of the landward 1/3 of fetch reach.
   b. If no bathymetry data are available, use a parameter estimating average shallow water depth in "meters below MTL"
6. Calculate wave energy density *E* using fetch *x*, wind speed *U* and water level *d* from (Young and Verhagen 1996, their eq. (25)).

   By using non dimensional variables: $\varepsilon = g^2E/U^4$ the non-dimensional energy, $\delta = gd/U^2$ the non-dimensional water depth and $\chi = gx/U^2$ the non-dimensional fetch; with *g* the gravitational acceleration.

$$\boxed{\varepsilon = 3.64 \times 10^{-3}\left[A_1 \tanh\left(\frac{B_1}{A_1}\right)\right]^{1.74}}$$

   where

$$A_1 = \tanh\left(0.493 \cdot \delta^{0.75}\right)$$
$$B_1 = 3.13 \times 10^{-3}\chi^{0.57}$$

7. Calculate the group wave power density P_w as

$$\boxed{P_w = c_g E}$$

   where

$$c_g = \frac{1}{2}c_p\left(1 + \frac{2kd}{\sinh(2kd)}\right) \qquad \text{wave group celerity, and}$$

$$c_p = \frac{\lambda}{T} = \left(\frac{g}{k}tanh(kd)\right)^{1/2} \qquad \text{wave celerity, and}$$

   k the wave number k=2π/λ, λ=wave length, T the wave period (Dingemans 1997, p. 49)

   a. Calculate wave period (Young and Verhagen 1996, eq. (28))

      By using non dimensional frequency $\nu = fU/g$

$$\boxed{\nu = 0.133\left[A_2 \tanh\left(\frac{B_2}{A_2}\right)\right]^{-0.37}}$$

      where

$$A_2 = \tanh\left(0.331 \cdot \delta^{1.01}\right)$$
$$B_2 = 5.215 \times 10^{-4}\chi^{0.73}$$

b. Calculate approximate wave length using the Hunt's method (Hunt 1979)

The wave celerity equation: $\lambda = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{\lambda}\right)$ can be approximated to

$$\boxed{\lambda = T\sqrt{\frac{gd}{F}}}$$

where

$$F = G + (1 + 0.6522 \cdot G + 0.4622 \cdot G^2 + 0.0864 \cdot G^4 + 0.0675 \cdot G^5)^{-1}$$

and

$$G = \left(\frac{2\pi}{T}\right)^2 \frac{d}{g}$$

This gives the wavelength to an accuracy of 0.1%.

c. Calculate wave group celerity C_g

d. Calculate wave power density P_w

8. Calculate the cell direction. This direction (α) is perpendicular to the side of the square raster cell that is facing water. If more than one side of the raster is adjacent to water then erosion from that direction is additively considered.

9. Calculate the incident power

$\boxed{P_i = P_w \cdot cos\alpha}$ α = angle between wind direction and marsh aspect from 8.

10. Calculate the mean-annual power contribution
 - Consider annual duration fraction, ω_f
 - Consider weight of water level, ω_l (now set to 0.2 as five water levels are considered)
 - If water level < *h*, the marsh scarp (Tonelli et al. 2010), then calculate mean annual incident power as

$$\boxed{\bar{P}_i = \omega_f \cdot \omega_l \cdot P_i}$$

11. Sum all wind contributions from all directions and speeds, $\boxed{\bar{P}_i^{tot} = \sum \bar{P}_i}$

12. Estimate the horizontal erosion rate as (Marani et al. 2011)

$$\boxed{R = a\frac{\bar{P}_i^{tot}}{h}}$$

where a is the volumetric annual erosion rate per unit mean annual incident wave power and it is user defined.

If the marsh scarp is not available, then a/h can be a user-input coefficient that depends on location/marsh type/marsh substrate

While this wave-power method provides significant additional sophistication to marsh-edge erosion estimates in SLAMM, there provide several important limitations to the wave-power estimates derived above. From a thesis by Mariotti (2013), the following limitations apply:

- This approach assumes uniform water level throughout the basin;
- The approach assumes steady wave conditions;
- The approach assumes constant water depth along the fetch during wave propagation;
- It assumes that there is no interaction between waves and currents.

Simple Erosion Model

Under equilibrium conditions, erosion and deposition balance and wetlands are not lost. However, historic sea-level rise coupled with local subsidence has upset coastal equilibrium in many parts of the world (Bird, 1986; Bruun, 1986). SLAMM has a very simple erosion model incorporated in which qualitative relationships are defined and used as thresholds for including constant rates of wave erosion in simulating the localized loss of wetlands. In the present implementation (SLAMM 6), marsh and beach erosion is triggered only when the average fetch of a cell exceeds 9 km (Knutson et al., 1981). Maximum fetch is calculated on a cell-by-cell basis at the beginning of each model time-step. Sixteen points of the compass are examined for every cell that borders on water (each 22.5 degrees). The maximum length of open water is calculated after examining all of these vectors. Tidal-flat erosion is assumed to occur at the open-water interface regardless of its calculated fetch.

Erosion is only predicted to occur at a land-cover to open water interface. Horizontal erosion rates may be specified as a function of marsh type and may be specified to vary spatially using "subsite polygons." For each site or subsite, erosion parameters for tidal flats, marshes, and swamps may be specified. Tidal-flat erosion rates pertain to both tidal flats and estuarine beaches (if the beach has adequate fetch to trigger erosion). The tidal-flat erosion parameter also pertains to ocean beaches if the Bruun rule is not being implemented. The marsh erosion parameter pertains to the interface between open water and regularly- and irregularly-flooded marshes as well as transitional marshes. The swamp erosion parameter pertains to all swamp types as well as mangrove swamps.

Ocean-Beach Erosion

Ocean-Beach erosion may optionally be modeled using a simplified relationship reported by Bruun in an analysis of coastal Florida (Bruun, 1962) whereby recession is 100 times the relative change in sea level. This option is retained for backward compatibility and is less frequently used than the other erosion models detailed above.

$$Recession = 100 \cdot SLRise \qquad \textbf{(12)}$$

where

Recession = width of beach lost during a time step (m);

The distance from the front edge of each beach cell to open ocean is calculated and the amount of recession in the relevant cell can then be computed:

$$Erosion_{Cell} = Recession - Distance \qquad \textbf{(13)}$$

where

$Erosion_{Cell}$ = Erosion of beach in current cell (m);
Distance = Distance from front edge of cell to open ocean (m);

The fraction of ocean beach lost for that cell is therefore

$$Fraclost_{OceanBeach} = \frac{Erosion_{Cell}}{Width_{OceanBeach,Cell}} \qquad \textbf{(14)}$$

where

$FracLost_{Ocean\ Beach}$ = Fraction of ocean beach lost in cell (unitless);
$Width_{Ocean\ Beach,\ Cell}$ = Original width of ocean beach in cell (m);

If the Bruun rule is not utilized then the “T. Flat Erosion” parameter is utilized to calculate horizontal beach erosion given adequate maximum fetch (9 km).

Soil Saturation

For undeveloped dry land, soil saturation can occur as a response of the fresh-water table to rising sea levels close to the coast.

Important Note: SLAMM 6 assumes no soil saturation of developed land because of the potential for the construction of drainage canals or the delivery of fill. Also note that the soil saturation model may be turned off in the “Execution Options” window of the model.

First, the height of the fresh-water table is estimated based on the nearest adjacent freshwater wetlands. If a dry land cell is within 6km of open ocean, and a contiguous width of 500 meters of fresh marsh, swamp, or fresh water is found between the dry land and the open ocean, then the water table for the dry land cell is estimated as follows:

$$WaterTable = MinElev_{NearWetland} + (SLRise / 0.91) \cdot e^{-0.776 - (0.0012\ Distance)} \qquad \textbf{(15)}$$

where:

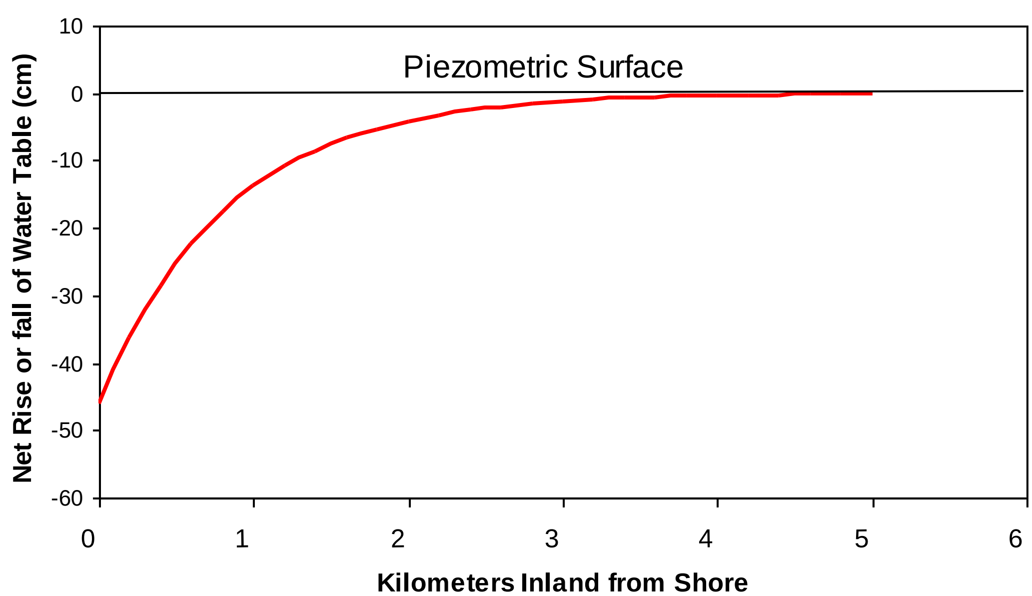
WaterTable	=	Estimated water table at the current dry land cell (m);
$MinElev_{NewrWetland}$	=	The elevation of the nearest wetland between the dry land and the open ocean (m);
SLRise	=	Sea-level rise during time step (m);
0.91	=	Tidal range from Carter et al., 1973 (m);
Distance	=	Distance from the cell to saltwater (m).

Equation **(12)** is adapted from Carter et al. (1973, figure VII-16). Figure 7 below shows the predicted extent of water table migration due to each 0.91 meters of sea level rise.

If the estimated water table becomes greater than the elevation of the dry land, saturation is predicted to take place. The fraction lost is calculated as a function of the slope of a cell, the current elevation of the (undeveloped) dry land, and the height of the water table. Conversion is to the nearest fresh marsh, swamp, or fresh-water type between the dry land and the open ocean.

SLAMM 6 does not predict soil saturation for dry land above 10 meters in elevation. This is designed to avoid overpredictions at higher elevations if wetlands are present due to a "perched water table" that would not be subject to effects from to a rise in the ocean water. Future implementations of this soil-saturation model would benefit from spatial water table data inputs rather than relying on an estimate based on nearby wetland elevations.

Figure 7: Water Table Rise Near Shore, Based on Carter et al., 1973



Accretion

Within the SLAMM model, "accretion" is used as a catch-all phrase to represent marsh-elevation change under different rates of sea-level rise, including shallow subsidence.

From Kirwan et al. : "…coastal ecosystems are known to be highly dynamic environments that have significant capacity to adjust to changes in rates of SLR through non-linear feedback mechanisms. In tidal marshes and mangroves, for example, increasing inundation leads to higher rates of sediment deposition, which helps tidal wetlands keep up with SLR (Reed 1995). In salt marshes, vegetation growth is typically more rapid at low elevations and in years of anomalously high sea level (Morris et al. 2002), potentially enhancing sediment trapping and organic matter accretion, and limiting erosion (Fagherazzi et al. 2004). These types of ecogeomorphic feedbacks likely explain the persistence of wetlands within the intertidal zone over thousands of years in the stratigraphic record (Redfield 1972), and observations of accretion rates that are highest in regions with historically high rates of SLR (Cahoon et al. 2006)." (2010).

In order to account for these feedbacks, in SLAMM accretion rates are modeled as third order polynomial function of cell elevation:

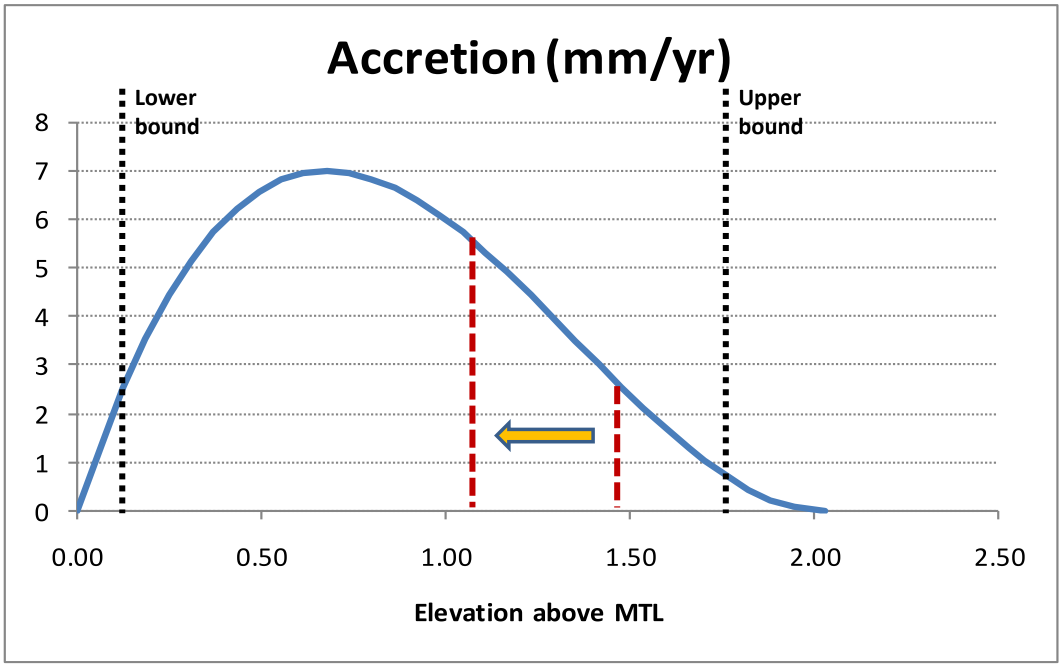
$$AccrRate = aH^3 + bH^2 + cH + d \qquad \textbf{(16)}$$

where:

AccrRate	=	Rate of predicted elevation change (mm/yr);
H	=	Height of cell divided by half of the GT tide range (half-tide units)
a,b,c,d	=	User input parameters describing the polynomial equation*;*

Figure 8 shows an example accretion curve in blue. The dotted red vertical lines show that with increased sea level, cell elevations can decrease and as a result accretion rates can increase as a response to increased inundation.

Figure 8: Generalized Accretion Feedback Curve as adapted from Morris (2007)
The yellow arrow illustrates how accretion rates on the vertical axis could increase as a marsh is flooded more regularly under SLR due to a lower elevation within the "tidal frame."



The description of marsh accretion by eq. (16) is general and flexible with respect to data availability. For example, a simple constant accretion response can be modeled by setting $a=b=c=0$ and $d=AccrRate$. Alternatively, polynomial parameters can be estimated by fitting the accretion function parameters to available accretion measurements and marsh platform elevations.

A more sophisticated approach can be to first model accretion by calibrating a mechanistic accretion model such as the Marsh Equilibrium Model (MEM) (Morris et al. 2002). A mechanistic model can be calibrated using available physical and biological data affecting accretion (e.g. tide ranges, suspended sediment concentrations, concentration density of standing biomass, organic matter decay rates, belowground biomass, and observed accretion rates). Once the model calibration is established, results can be translated into polynomial curves that are a function of marsh elevation, and these curves can be entered into SLAMM.

Shallow subsidence and soil compaction should be included in any model or data analysis describing "accretion rates" within SLAMM. Deeper subsidence would be modeled based on the difference between relative sea-level rise and eustatic sea-level rise or using spatially-variable land-movement maps.

Four separate accretion-feedback models are available for "regularly-flooded marsh," "irregularly-flooded marsh," "tidal flats," and "tidal-fresh marsh" categories. Vertical movement of other habitats (Inland-Fresh Marsh, Mangrove, Swamps, and Beaches) are modeled as constants ("elevation gain in mm/year") though with a minor source-code modification a feedback model as shown above can be (and has been) used for these categories when adequate data or models are available.

Salinity Module

The SLAMM salinity model estimates a spatial map of salinity under conditions of low tide, mean tide, high tide, and flood tide (water at "salt elevation"). Considerations of salinity may be required when modeling marsh fate as marsh-type is often more highly correlated to water salinity than elevation when fresh-water flow is significant (Higinbotham et. al, 2004). Predicted salinity may also have effects on accretion rates as detailed above. The SLAMM model attempts to predict mean salinities without the requirement for input-data-intensive and computationally-intensive three dimensional hydrodynamic models. In the near future, a capability to link the SLAMM model to spatial model output from more complex salinity models will be released as part of SLAMM 6. The existing SLAMM model remains fairly experimental and simple in nature, though it has successfully been calibrated to salinity data in Georgia and Washington State.

The SLAMM salinity model assumes a salt wedge setup within an estuary. Water heights are estimated as a function of tide range, mean tide level, fresh water flow, and calculated fresh water retention time. The depth of the salt wedge is estimated as a function of river mile, the slope of the salt wedge, and the tide level, and sea level rise.

After an initial condition has been successfully captured, the model may be run with an increased sea level to predict the salinity changes under this condition. The model has been calibrated to effectively capture salinity variations under existing conditions but validation of model predictions under conditions of SLR has not yet been undertaken.

Input Parameters

- River domains and tributary pathways are defined by the user (center of the river channel).
- The user has the capability to enter a time-series of fresh water flows for each river and tributary.
- Bathymetry is also an important model input. This does not require additional data structures, but the user may enter water depths in locations that are permanently covered in water and the model now interprets those elevations as part of the salinity calculations.
- Salinity of fresh and salt waters are two additional model parameters.
- The slope of the salt wedge is assumed to be linear and serves as a calibration parameter for this model.
- The origin of the salt wedge may also be specified as a function of "river km" calculated with kilometers increasing when moving from the defined origin to the mouth of the river. If this parameter is not specified, the origin is set to the most oceanic defined extent of fresh water influence.
- An optional turbidity factor time-series may also be specified that is treated as a multiplier to accretion rates specified or calculated as detailed above.

Within the boundaries of fresh-water influence, salinities will be solved for each cell as though equilibrium has been allowed to occur at the time of MHHW, mean tide, and MLLW. Based on the height of water within each cell, a mix of salt water and fresh water can be calculated and an overall salinity derived.

$$Salinity_{cell} = 0.75(Salinity_{SaltWater} * fraction_{SaltWater} + Salinity_{FreshWater} * fraction_{FreshWater}) + 0.25(Salinity_{Segment}) \quad \textbf{(17)}$$

where

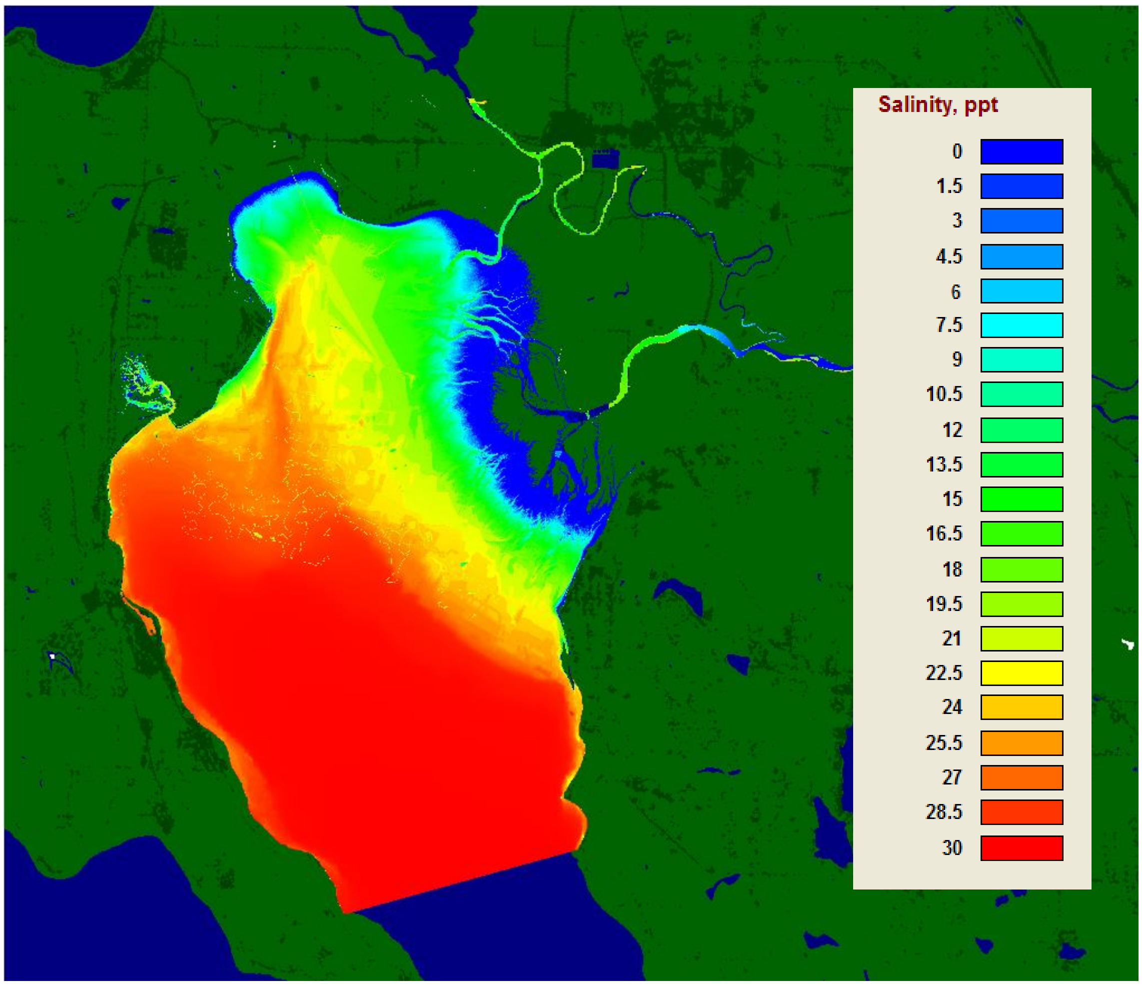
$Salinity_{Cell}$	=	the estimated salinity of a cell at a given tide;
$fraction_{SaltWater}$	=	the estimated height of salt water as a function of total water height;
$Salinity_{SaltWater}$	=	salinity of salt water, user input (ppt);
$Salinity_{Segment}$	=	calculated salinity of the cross section area the cell resides in—assumes some mixing effects at times the salt wedge breaks down;
$fraction_{FreshWater}$	=	1- $fraction_{SaltWater}$

Within the river itself, the river's cross section perpendicular to each segment of the water is calculated as a function of the river's bathymetry. Fresh water flows are assumed distributed across this river basin. Salinity will intrude up the estuary when elevations and mean tide range permit and salinities then calculated. The cross-sectional salinity ($Salinity_{Segment}$ above) is estimated by calculating the volume of fresh water and volume of salt water in each cross-sectional segment and calculating the weighted-average salinity for the entire cross section.

Within the estuary where river flows are defined, fresh water is distributed using the following set of assumptions.

- Salt water heights are calculated as a function of tidal height, salt wedge slope and cell elevation.
- The salt wedge is estimated to migrate horizontally 4.82 km per meter of vertical tide or SLR based on data from five Georgia estuaries.
- If fresh-water flows change, the salt wedge slope is predicted to be affected by those changes. The slope will increase by 2.8E-7 for each additional CFS of fresh water following the initial-condition calibration. The slope will decrease by the same factor for each loss of CFS. This construct allows further penetration of salinity upriver during periods of low flow and is based on data from four major Georgia estuaries.
- Fresh water is distributed based on vector of flow into the estuary and bathymetry of estuary.
- River segments are derived and "f-tables" or volume to depth relationships are derived for each segment as a function of the river's bathymetry. Beyond the main channel flow, segments are defined in semi-circular fashion and similar f-tables are derived.
- Salt water elevations are estimated as a function of the tide range, the slope of the salt wedge and the distance to the end of the salt wedge which is defined by the user or assumed to be the limit of freshwater flow influence. (Salt elevations may be examined in "debug mode" along with predicted salinity maps and river kilometer designations.)
- Water elevations are predicted as a function of the cell's mean tide level, the spatially variable tide-range, and the tide range being examined.
- An initial condition "retention time" is calculated based on the physical setup described above. In the case of changes in freshwater flow, variable fresh water is distributed to each river segment as a function of this calculated retention time.

- Complex hydrodynamic processes such as water density effects, conservation of momentum, advection and diffusion are not explicitly included in this model. A capability to link the SLAMM model to spatial model output from more complex salinity models is also available within SLAMM.



Predicted Mean Tide Level Salinities for Port Susan Bay

Operationally, the SLAMM Salinity model works as follows:

At Time Zero

1. Calculate the *salt height*$_{\text{Tide}}$ of the estuary segment N as a function of tide and slope of the salt wedge.
2. Calculate the *retention time*$_{\text{Tide}}$ of estuary segment N as a function of fresh water volume
    a. *Height of fresh water*$_{\text{Tide}}$ = water height – salt height
    b. *Volume of fresh water*$_{\text{Tide}}$ = volume (fresh height) – volume (salt height) using F-Table derived from bathymetry
    c. *Retention time*$_{\text{Tide}}$ = *Volume of fresh water*$_{\text{Tide}}$ (m3) / Flow of fresh water at river mouth (m3/d)
3. Calculate *Salinity*$_{Cell}$ as a function of salt water and fresh water volumes as shown in **(15)**.

At Time T

1. *salt height*$_{\text{Tide}}$ of the estuary segment N is calculated based on change in MTL (SLR), and changes in the salt wedge location as a function of fresh water flows and SLR. Tidal range assumed to remain constant.
2. *retention time*$_{Tide}$ modified as a function of previous retention time and modifications to river area in the given segment
3. Calculate water level of the Estuary segment N
    a. Salt volume from water volume, salt elevation
    b. Fresh volume = *flow*$_{\text{TN}}$ * *retention time*
    c. Water height = FTable height (Salt Volume + Fresh Volume)
4. Calculate Cell Salinities$_{\text{Tide}}$ as a function of salt water and fresh water volumes.

$$saltheight_{Tide}=TideHeight\text{-}(OrgRn\text{-}RSeg)\cdot SliceIncrement\cdot 1000\cdot SaltWedgeSlope \quad \textbf{(18)}$$

$$retentiontime_{Time-zero}=\frac{Volume_{FreshWater}}{Flow_{FreshWater}} \quad \textbf{(19)}$$

$$Volume_{FreshWaterTN}=\frac{Flow_{FreshWaterTN}}{RetentionTime} \quad \textbf{(20)}$$

where

saltheight$_{Tide}$	=	the estimated elevation of the salt wedge in meters;
TideHeight	=	MLLW, MTL, or MHHW in meters;
OrgRn	=	the origin of the salt wedge defined by the user or the maximum river segment number with freshwater influence. The location of this segment migrates inland by 4.82 km per meter of SLR and/or meter of tidal influence.
Rseg	=	the current river segment number;
SliceIncrement	=	the size of each river slice in kilometers;
1000	=	meters per kilogram;
SaltWedgeSlope	=	user input slope of the salt wedge in (m/m). This slope may be modified if fresh water flow is variable as specified above;

Retentiontime	=	predicted retention time for fresh water for each segment at each tide level (s);
$Volume_{FreshWater}$	=	volume of fresh water in each segment (m^3);
$Flow_{FreshWater}$	=	user input time varying fresh water flow (m^3/s).

Linkage of Data from Salinity Models

There are two methods of linking data from existing hydrodynamic salinity models into SLAMM—a raster method and a point-data method.

A series of salinity rasters may be used in which salinity for each cell is specified for each year of a simulation. To do this, a salinity "base file" in the file setup window should be specified. This raster will represent the initial condition-- other years will be specified as part of the raster file-names adding the year before the file extension. An example of such a series of file names would be "SALINITY.ASC" as a base file name followed by "SALINITY2025.ASC" "SALINITY2050.ASC" etc.

The second option consists of linking SLAMM to an Excel file in which a series of station locations is specified for an estuary. On the second tab of the spreadsheet, a set of data describing salinity as a function of RSLR, flow, and station location must be specified. At each time step and for each cell, the SLAMM model will interpolate data between station locations and between modeled levels of RSLR. This point-data linkage model was originally designed to link output from the CE-QUAL-W2 model into SLAMM.

At this time, the point-data method may only be used within a single defined estuary in a SLAMM simulation. For that (first) "freshwater flow" polygon within a SLAMM simulation, a user may specify a single flow or a time-series of flow data. SLAMM will then match the predicted flow at a given time step with the flow scenarios included in the spreadsheet. At this time, the specified flow-rate in SLAMM must match the flow data in the spreadsheet precisely—SLAMM will not interpolate between different rates of flow.

With either of these salinity-linkage options, the unit of salinity is assumed to be "ppt" though this is not a strict requirement due to the flexibility in setting up salinity habitat-switching rules. Salinity data may be passed into SLAMM at whatever tide (or aggregated set of tides) that is considered most influential to habitat switching.

After salinity data have been linked to SLAMM using either of these two model options, salinity data and salinity histograms describing relationships between salinity and habitat type may be produced within the model interface. Then a set of rules describing habitat switching as a function of salinity may be set up. For more information on how to set up these linkage options in the model interface, please see the User's Manual.

Habitat Switching Functions

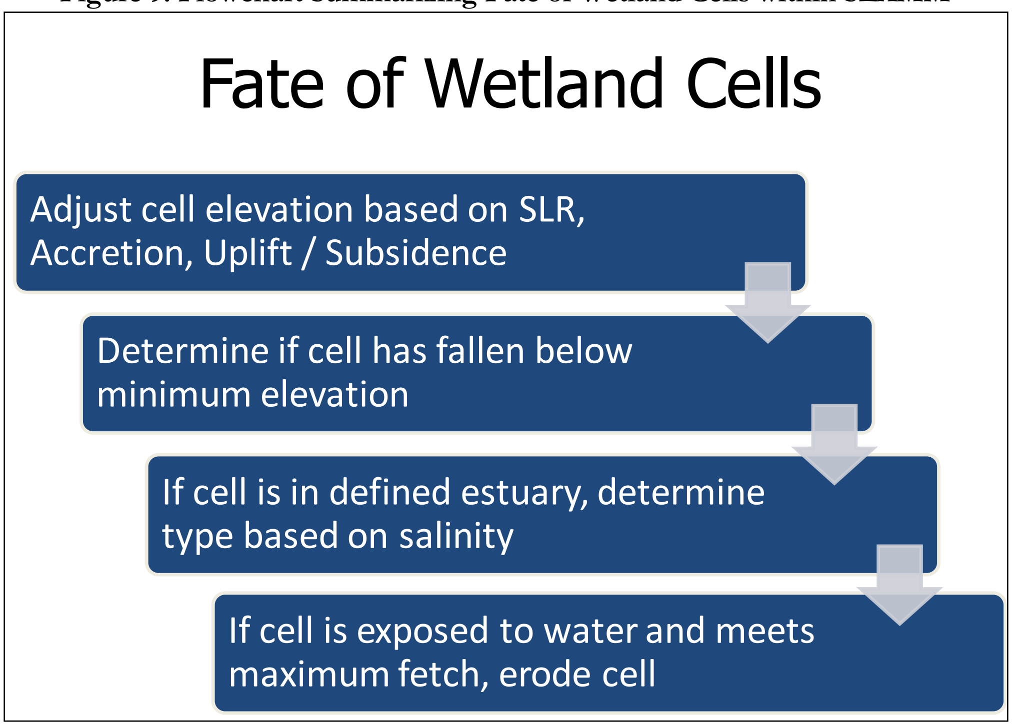
Habitat switching functions (as a function of elevation) have been made flexible to allow site specific information to inform model-predicted succession.

For example, the work of McKee and Patrick (1988) forms the basis for SLAMM saltmarsh elevation as a function of tidal range. However, within this paper, site specific anomalies are visible. Site-specific LiDAR data provides us with a capability to evaluate current model assumptions and to calibrate the model's elevation ranges for local conditions. Elevation ranges for each land-cover type are new model inputs in the new version of SLAMM.

In locations where elevation ranges of marsh types overlap considerably (generally locations with a significant fresh-water signal) the salinity model as described above has been used to differentiate marsh type. Similar to the elevation model, salinity ranges are editable by the user to allow habitat switching as a function of salinity. Salinity statistics and histograms are also available directly through the SLAMM user interface. Salinity rules may be specified describing at which level of salinity and at which tide habitat switching is predicted to occur. The most common set of rules for habitat switching as a function of salinity pertain to Tidal Swamps becoming Tidal Fresh Marsh as salinity increases, Tidal Fresh Marshes converting to Brackish (irregularly-flooded) marshes, and then Brackish Marshes converting to Salt (regularly-flooded) Marshes.

Figure 9 illustrates the fate of wetland cells as calculated within SLAMM. A detailed category-by category accounting of assumptions regarding wetland cells and habitat switching may be found at the end of this document.

Figure 9: Flowchart Summarizing Fate of Wetland Cells within SLAMM



Submerged Aquatic Vegetation (SAV) model

SLAMM uses a regression relationship developed by Melanie Frazier and Patrick Clinton of U.S. EPA to describe the probability of submerged aquatic vegetation being present in a given cell. The default parameters as delivered with SLAMM 6.7 were derived using data from the Yaquina estuary in Oregon and the relationship was then validated at the Tilamook and Alsea estuaries in Oregon.

$$\begin{aligned} Logit = {} & Intcpt + DEM \cdot C_{DEM} + DEM^{2} \cdot C_{DEMSQ} + DEM^{3} \cdot C_{DEMCubed} + \\ & D2MLLW \cdot C_{MLLW} + D2MHHW \cdot C_{MHHW} + \\ & D2Mouth \cdot C_{D2Mouth} + D2Mouth^{2} \cdot C_{D2MouthSq} \end{aligned} \tag{21}$$

$$PROBSAV = \frac{1}{1+e^{-Logit}} \tag{22}$$

where

PROBSAV	=	the probability a cell has SAV, estimated elevation of the salt wedge in meters, (fraction from 0.0 to 1.0);
Intcpt, $C_{DEM,\ MLLW,\ etc.}$	=	various user-defined coefficients (unitless);
DEM	=	DEM with a vertical datum of NAVD88 (meters);
D2Mouth	=	distance to estuary mouth in meters as defined by a fixed user-input raster. Cost-path methodology has been used in the past;
D2MLLW,MHHW	=	distance to mean lower low water or mean higher high water for each cell as derived by SLAMM in each time step (meters);

When this model is implemented, probability-of-SAV maps may be produced by the model in each time step. The expected value of total SAV habitat in square kilometers is output along with other SLAMM tables of output in the default comma-separated-variable (CSV) file produced.

Infrastructure – Roads Module

In 2012 the US Fish and Wildlife Service funded the addition of a roads module to SLAMM. This allows model users in input the location, elevation, and class of road infrastructure in a study area (see the User's Manual for more details), and to obtain estimations of the road system vulnerability with respect to sea level rise.

SLAMM first updates cell elevations to account for specific road elevations within each cell containing road portions. During the simulation, SLAMM searches for water inundation paths using the road inundation algorithm to estimate the 30, 60, 90 days frequency of inundation for the road network (see *Connectivity* on page 24 for further details).

At the end of a SLAMM simulations numerical data of the total length of roads that are inundated <30, 30-60, 60-90 days are summarized in the output excel file. Infrastructure data may be directly loaded into the SLAMM model from shape files that have the same projection as the rasters utilized. Full specifications of how to use the module may be found in the *SLAMM 6.7 User's Manual.*

The SLAMM Decision Trees

"Traditional SLAMM simulations"

Traditional SLAMM simulations have not changed from version 6.6 to 6.7, but the internal data structure has been made more flexible to allow categories to be edited through the source code easily and in the near future, through the graphical user interface.

Table 3 summarizes the characteristics of each land type. A discussion of how each SLAMM land-cover category is processed then follows.

For "Traditional" SLAMM simulations, tropical systems are defined as sites containing 0.5% or more total land coverage by mangroves. In these systems any land inundated with saline water is assumed to convert to a mangrove forest.

"California SLAMM simulations"

Table 4 summarizes the characteristics of each land type in the new California model. A discussion of how each SLAMM land-cover category is processed then follows. A complete crosswalk between California NWI codes and the relevant CA SLAMM land-cover category is provided in Appendix A of this document.

Table 3. Definitions and Specifications for "Traditional SLAMM" Categories

Category Name	GIS Number	Open Water	Tidal	Non-Tidal Wet.	Dry Land	Dev-eloped	Aggregation Category	IFM Collapse	RFM Collapse	Accretion Model	Erosion Model
Developed Dry Land	1				X	X	Aggregated Non Tidal			None	No Erosion
Undeveloped Dry Land	2				X		Aggregated Non Tidal			None	No Erosion
Swamp	3			X			Freshwater Non-Tidal			Swamp	Swamp Erosion
Cypress Swamp	4			X			Freshwater Non-Tidal			Swamp	Swamp Erosion
Inland-Fresh Marsh	5			X			Freshwater Non-Tidal			Inland Marsh	No Erosion
Tidal-Fresh Marsh	6		X				Freshwater Tidal			Tidal-Fresh Marsh	Marsh Erosion
Trans. Salt Marsh	7		X				Transitional	X		Irreg.Flood.Marsh	Marsh Erosion
Regularly-Flooded Marsh	8		X				Saltmarsh		X	Reg.Flood.Marsh	Marsh Erosion
Mangrove	9		X				Transitional			Mangrove	Swamp Erosion
Estuarine Beach	10		X				Low Tidal			Beach/T.Flat	T.Flat Erosion
Tidal Flat	11		X				Low Tidal			Beach/T.Flat	T.Flat Erosion
Ocean Beach	12		X				Low Tidal			Beach/T.Flat	Ocean Beach Erosion
Ocean Flat	13		X				Low Tidal			Beach/T.Flat	T.Flat Erosion
Rocky Intertidal	14		X				Low Tidal			None	No Erosion
Inland Open Water	15	X					Open Water			None	No Erosion
Riverine Tidal	16	X	X				Open Water			None	No Erosion
Estuarine Open Water	17	X	X				Open Water			None	No Erosion
Tidal Creek	18	X	X				Open Water			None	No Erosion
Open Ocean	19	X	X				Open Water			None	No Erosion
Irreg.-Flooded Marsh	20		X				Transitional	X		Irreg.Flood.Marsh	Marsh Erosion
Inland Shore	22		X				Freshwater Non-Tidal			None	No Erosion
Tidal Swamp	23		X				Freshwater Tidal			Tidal Swamp	Swamp Erosion
Flooded Developed Dry Land	25		X			X	Aggregated Non Tidal			None	No Erosion
Flooded Forest	26		X				Transitional			None	No Erosion

Inundation Models for "Traditional SLAMM" Categories:

- **[1] Developed Dry Land:** When it falls below its lower elevation boundary, this category generally converts to "Trans. Salt Marsh." However, (1) Do not inundate if Protect All Dry Land is selected. Otherwise, (2) Do not inundate if Protect Developed Dry Land is selected. Otherwise, (3) If "Use Flooded Developed" is selected then inundate to flooded developed dry land. Otherwise, (4) If "AdjOcean" and ocean water is nearer than estuarine water then convert to ocean beach. Otherwise, (5) If "AdjWater" with a fetch > 20 km then inundate to estuarine beach. Otherwise, (6) If site is designated as tropical and cell is "NearWater" then inundate to mangrove. Otherwise, (7) If the cell is "fresh water influenced" then convert to tidal swamp.

- **[2] Undeveloped Dry Land:** When it falls below its lower elevation boundary, this category generally converts to "Trans. Salt Marsh." However, (1) Do not inundate if Protect All Dry Land is selected. Otherwise, (2) If "AdjOcean" and ocean water is nearer than estuarine water then convert to ocean beach. Otherwise, (3) If "AdjWater" with a fetch > 20 km then inundate to estuarine beach. Otherwise, (4) If site is designated as tropical and cell is "NearWater" then inundate to mangrove. Otherwise, (5) If the cell is "fresh water influenced" then convert to tidal swamp.

- **[3] Swamp:** When it falls below its lower elevation boundary, this category generally converts to "Trans. Salt Marsh." However, (1) If the cell is "fresh water influenced" then convert to tidal swamp. Otherwise, (2) If site is designated as tropical and cell is "NearWater" then inundate to mangrove.

- **[4] Cypress Swamp:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water." However, (1) If "Use Flooded Forest" is selected then inundate to "flooded forest." Otherwise, (2) If site is designated as tropical and cell is "NearWater" then inundate to mangrove.

- **[5] Inland-Fresh Marsh:** When it falls below its lower elevation boundary, this category generally converts to "Trans. Salt Marsh." However, (1) If the cell is "fresh water influenced" then inundate to tidal fresh marsh. Otherwise, (2) If site is designated as tropical and cell is "NearWater" then inundate to mangrove.

- **[6] Tidal-Fresh Marsh:** When it falls below its lower elevation boundary, this category generally converts to "Tidal Flat." However, (1) If site is designated as tropical and cell is "NearWater" then inundate to mangrove. Otherwise, (2) If the cell elevation is above than the lower bound for transitional marsh then convert to transitional marsh. Otherwise, (3) If the cell elevation is above than the lower bound for regularly-flooded marsh then convert to regularly-flooded.

- **[7] Trans. Salt Marsh:** When it falls below its lower elevation boundary, this category generally converts to "Regularly-Flooded Marsh." However, (1) If site is designated as tropical then inundate to mangrove.

- **[8] Regularly-Flooded Marsh:** When it falls below its lower elevation boundary, this category generally converts to "Tidal Flat." However, (1) If site is designated as tropical then inundate to mangrove.

- **[9] Mangrove:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water."
- **[10] Estuarine Beach:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water."
- **[11] Tidal Flat:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water."
- **[12] Ocean Beach:** When it falls below its lower elevation boundary, this category generally converts to "Open Ocean."
- **[13] Ocean Flat:** When it falls below its lower elevation boundary, this category generally converts to "Open Ocean."
- **[14] Rocky Intertidal:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water." However, (1) If "AdjOcean" then inundate to open ocean.
- **[15] Inland Open Water:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water."
- **[16] Riverine Tidal:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water."
- *[17] Estuarine Open Water: inundation model is not relevant for this category.*
- *[18] Tidal Creek: inundation model is not relevant for this category.*
- *[19] Open Ocean: inundation model is not relevant for this category.*
- [20] Irreg.-Flooded Marsh: When it falls below its lower elevation boundary, this category generally converts to "Regularly-Flooded Marsh." However, (1) If site is designated as tropical then inundate to mangrove.
- **[22] Inland Shore:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water." However, (1) If "AdjOcean" then inundate to open ocean.
- **[23] Tidal Swamp:** When it falls below its lower elevation boundary, this category generally converts to "Irreg.-Flooded Marsh." However, (1) If the cell is "fresh water influenced" then inundate to tidal fresh marsh. Otherwise, (2) If site is designated as tropical and cell is "NearWater" then inundate to mangrove.
- *[25] Flooded Developed Dry Land: inundation model is not relevant for this category.*
- *[26] Flooded Forest: inundation model is not relevant for this category.*

Table 4. Definitions and Specifications for "California SLAMM" Categories

Category Name	GIS Num	Open Water	Tidal	Non-Tidal Wetland	Dry Land	Dev-eloped	Aggregation Category	IFM Col.	RFM Col.	Accretion Model	Erosion Model
Developed Dry Land	101				X	X	Aggregated Non Tidal			None	No Erosion
Undeveloped Dry Land	102				X		Aggregated Non Tidal			None	No Erosion
Agriculture	103				X		Aggregated Non Tidal			None	No Erosion
Artificial Pond	104						Freshwater Non-Tidal			None	No Erosion
Artificial Salt Pond	105						Open Water			None	No Erosion
Inland Open Water	106						Freshwater Non-Tidal			None	No Erosion
Inland Shore	107						Freshwater Non-Tidal			None	No Erosion
Freshwater Marsh	108			X			Freshwater Non-Tidal			Inland Marsh	No Erosion
Seasonal Freshwater Marsh	109			X			Freshwater Non-Tidal			Inland Marsh	No Erosion
Seasonally Flooded Agriculture	110						Freshwater Non-Tidal			None	No Erosion
Dunes	111						Aggregated Non Tidal			None	No Erosion
Freshwater Forested/Shrub	112			X			Freshwater Non-Tidal			Swamp	Swamp Erosion
Tidal Freshwater Forested/Shrub	113		X				Freshwater Tidal			Tidal Swamp	Swamp Erosion
Tidal Fresh Marsh	114		X				Freshwater Tidal			Tidal-Fresh Marsh	Marsh Erosion
Irreg.-Flooded Marsh	115		X				Transitional	X		Irreg.Flood.Marsh	Marsh Erosion
Estuarine forested/shrub wetland	116		X				Transitional	X		Irreg.Flood.Marsh	Swamp Erosion
Artificial reef	117		X				Low Tidal			None	No Erosion
Invertebrate reef	118		X				Low Tidal			None	No Erosion
Ocean Beach	119		X				Low Tidal			Beach/T.Flat	Ocean Beach
Regularly-flooded Marsh	120		X				Saltmarsh		X	Reg.Flood.Marsh	Marsh Erosion
Rocky Intertidal	121		X				Low Tidal			None	No Erosion
Tidal Flat and Salt Panne	122	X	X				Low Tidal			Beach/T.Flat	T.Flat Erosion
Riverine (open water)	123	X					Open Water			None	No Erosion
Riverine Tidal	124	X	X				Open Water			None	No Erosion
Tidal Channel	125	X	X				Open Water			None	No Erosion
Estuarine Open Water	126	X	X				Open Water			None	No Erosion
Open Ocean	127	X	X				Open Water			None	No Erosion
Flooded Developed	128					X	Transitional			None	No Erosion

Inundation Models for "California SLAMM" Categories:

- **[101] Developed Dry land**: When it falls below its lower elevation boundary, this category generally converts to "Irregularly-flooded marsh." However, (1) Do not inundate if Protect All Dry Land is selected. Otherwise, (2) Do not inundate if Protect Developed Dry Land is selected. Otherwise, (3) If "Use Flooded Developed" is selected then inundate to flooded developed dry land. Otherwise, (4) If "AdjOcean" and ocean water is nearer than estuarine water then convert to ocean beach. Otherwise, (5) If the cell is "fresh water influenced" then convert to tidal forested/shrub. Finally, (6) If the cell is "Adjacent to Estuarine forested/shrub wetland," then convert to that category.

- **[102] Undeveloped Dry Land**: When it falls below its lower elevation boundary, this category generally converts to "Estuarine forested/shrub wetland." However, (1) Do not inundate if Protect All Dry Land is selected. Otherwise, (2) If "AdjOcean" and ocean water is nearer than estuarine water then convert to ocean beach. Otherwise, (3) If the cell is "fresh water influenced" then convert to tidal forested/shrub. Finally, (4) If the cell is "Adjacent to Estuarine forested/shrub wetland," then convert to that category.

- **[103] Agriculture**: Defaults to the same inundation model as above [102].

- **[104] Artificial Pond**: When it falls below its lower elevation boundary, this category converts to "Estuarine Open Water."

- **[105] Artificial Salt Pond**: When it falls below its lower elevation boundary, this generally converts to "Estuarine Open Water."

- **[106] Inland Open Water**: When it falls below its lower elevation boundary, this category converts to "Estuarine Open Water."

- **[107] Inland Shore**: When it falls below its lower elevation boundary, this category converts to "Estuarine Open Water."

- **[108] Freshwater Marsh**: When it falls below its lower elevation boundary, this category generally converts to "Irreg.-Flooded Marsh." However, (1) If the cell is "fresh water influenced" then inundate to tidal fresh marsh.

- **[109] Seasonal Freshwater Marsh**: When it falls below its lower elevation boundary, this category generally converts to "Irreg.-Flooded Marsh." However, (1) If the cell is "fresh water influenced" then inundate to tidal fresh marsh.

- **[110] Seasonally Flooded Agriculture**: When it falls below its lower elevation boundary, this category generally converts to "Irreg.-Flooded Marsh." However, (1) Do not inundate if Protect All Dry Land is selected. Otherwise, (2) If "AdjOcean" and ocean water is nearer than estuarine water then convert to ocean beach. Otherwise, (3) If the cell is "fresh water influenced" then convert to tidal forested/shrub.

- **[111] Dunes:** When it falls below its lower elevation boundary, this category converts to "Ocean Beach."

- **[112] Freshwater Forested/Shrub**: When it falls below its lower elevation boundary, this category generally converts to "Estuarine forested/shrub wetland." However, (1) If the cell is "fresh water influenced" then convert to tidal forested/shrub.
- **[113] Tidal Freshwater Forested/Shrub:** When it falls below its lower elevation boundary, this category generally converts to "Irreg.-Flooded Marsh." However, (1) If the cell is "fresh water influenced" then inundate to tidal fresh marsh.
- **[114] Tidal Fresh Marsh:** When it falls below its lower elevation boundary, this category generally converts to "Tidal Flat and Salt Panne." However, (1) If the cell elevation is above than the lower bound for irregularly-flooded marsh then convert to transitional marsh. Otherwise, (2) If the cell elevation is above than the lower bound for regularly-flooded marsh then convert to regularly-flooded.
- **[115] Irreg.-Flooded Marsh:** When it falls below its lower elevation boundary, this category converts to "Regularly-flooded Marsh."
- **[116] Estuarine forested/shrub wetland:** When it falls below its lower elevation boundary, this category converts to "Regularly-flooded Marsh."
- **[117] Artificial reef:** When it falls below its lower elevation boundary, this category converts to "Estuarine Open Water."
- **[118] Invertebrate reef:** When it falls below its lower elevation boundary, this category converts to "Estuarine Open Water."
- **[119] Ocean Beach:** When it falls below its lower elevation boundary, this category converts to "Open Ocean."
- **[120] Regularly-flooded Marsh:** When it falls below its lower elevation boundary, this category converts to "Tidal Flat and Salt Panne."
- **[121] Rocky Intertidal:** When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water." However, (1) If "AdjOcean" then inundate to open ocean.
- **[122] Tidal Flat and Salt Panne**: When it falls below its lower elevation boundary, this category generally converts to "Estuarine Open Water." However, (1) If "AdjOcean" then inundate to open ocean.
- **[123] Riverine (open water):** When it falls below its lower elevation boundary, this category converts to "Riverine Tidal." (Inundation models are questionably relevant for open-water categories and would require river bathymetry to properly estimate tidal influence.)
- *[124] Riverine Tidal: inundation model is not relevant for this category.*
- *[125] Tidal Channel: inundation model is not relevant for this category.*
- *[126] Estuarine Open Water: inundation model is not relevant for this category.*
- *[127] Open Ocean: inundation model is not relevant for this category.*
- *[128] Flooded Developed: inundation model is not relevant for this category.*

Freshwater Influence

As noted above, a polygon may be defined as having freshwater-flow influence without explicitly modeling salinity. After defining a fresh-water influenced region the habitat-switching flowchart becomes modified. In this modified habitat-switching flow chart **Dry Land** or **Swamp** converts to **Tidal Swamp**, **Tidal Swamp** converts to **Tidal Fresh Marsh**, and **Tidal Fresh Marsh** then converts to **Irregularly-Flooded Marsh**. In comparison, when no freshwater influence is defined, **Swamp** converts directly to **Irregularly-Flooded Marsh**.

To use the fresh water extent capability:

- Under Set Map Attributes, click "Show... Fresh Flows" at the upper left.
- Add a "fresh flow"
- Define the boundary with the "define boundary" button.
- **Click on "F.W. Extent Only" under that button**.
- Areas within the polygon you have defined will be subject to the flow chart as shown above.
- No other parameters are required.

Carbon Sequestration

SLAMM 6.7 estimates carbon sequestration as a function of land cover based on the approach developed by Vanderbroek and Crooks at ESA PWA (2014). This method accounts for both the amount of carbon sequestered by wetlands as well as the carbon emissions through the loss of methane from freshwater habitats. The calculation is composed of fours steps:

1. Calculate above ground carbon stock based on above ground biomass:

$$ST\_A = CF * AB\_A \quad \textbf{(23)}$$

where:

ST_A	=	Aboveground carbon stock, per area (metric tons C/ha)
CF	=	Carbon fraction of dry matter (assumed 0.47 for all land covers)
AB_A	=	Aboveground biomass, per area (metric tons dry matter/ha) – Landcover dependent, default values found in Table TBA.

2. Estimate cumulative CO_2 equivalents sequestered based on habitat area, change in aboveground carbon stock, and soil carbon storage rate:

$$CO2_t = \frac{44}{12} * \left[ST_t - ST_{tzero} + \sum_{tzero}^{t} \frac{(A_{t-DeltaT} + A_t)}{2} * SEQ_c * DeltaT \right] \quad \textbf{(24)}$$

where:

$CO2_t$	=	Cumulative CO2 sequestered at time t for specified habitat type (metric tons CO2 equivalents)

44/12	=	Ratio of molecular weight of CO2 to C (to convert mass of C to equivalent mass of CO2)
ST_t	=	Total aboveground carbon stock at time t (metric tons C) – from Step 1
A_t	=	Area of habitat at time t (hectares) – from SLAMM results
$A_{t\text{-}DeltaT}$	=	Area of habitat in previous time step (hectares) – from SLAMM results
SEQ_C	=	Soil carbon storage rate for specified habitat type (metric tons C/ha/year) – Landcover dependent, default values found in Table TBA.
DeltaT	=	Years since previous time step.

3. Estimate cumulative CH_4 emissions based on habitat area methane emission rate:

$$CH4_t = \sum_{2010}^{t} A_t * EM_{CH4} * DeltaT \quad \textbf{(25)}$$

where:

$CH4_t$	=	Cumulative CH4 emitted at time t for specified habitat type (metric tons CH4)
EM_{CH4}	=	Methane emission rate (metric tons CH4/ha/year) – Landcover dependent, default values found in Table TBA.

4. Combine CO_2 sequestration with CH_4 emissions to estimate the net greenhouse gas sequestration

$$GHG_t = CO2_t - 21*CH4_t \quad \textbf{(26)}$$

where:

GHGt	=	Cumulative GHG sequestered at time t (metric tons CO2 equivalents)

California Lagoonal Framework

This section of the SLAMM Technical documentation, written by ESA, describes a classification framework for California estuaries and a conceptual model of hydrology and land-cover classes for lagoon estuaries. This work draws upon ESA's experience with California estuaries as well as discussions, data analysis, site visits, and collaborative work with The Nature Conservancy (TNC) and Warren Pinnacle Consulting (WPC). This classification framework and conceptual model are being used by WPC to update the Sea-Level Affecting Marshes Model (SLAMM) for California with funding provided by TNC.

Types of California Estuaries

SLAMM was originally developed for and has primarily been applied to estuaries on the East Coast and Gulf Coast of the United States. While there are some instances of applying SLAMM to estuaries in California, these applications have typically required using existing East Coast land-cover classes as surrogates for California land-cover classes that were not defined until SLAMM Version 6.7.

In addition to different land-cover classes, many California estuaries have different hydrologic conditions as compared to East Coast estuaries. In particular, the mouth of many California estuaries is affected by a barrier beach. Barrier beaches are built by the littoral ocean processes of waves, tides, and sand transport. These barrier beaches can mute or entirely block tidal propagation into the estuary. When the tidal muting becomes significant, an estuary may be referred to as a lagoon. In addition to muting tidal propagation from the ocean, the barrier beach may also restrict the conveyance of fluvial discharge from the estuary to the ocean. This restriction causes water levels to back up behind the barrier beach, inundating elevations above the tide range. These inundated areas then influence wetland land-cover classes. Therefore, the water levels in many California estuaries, especially lagoon estuaries, do not match the ocean tides and vegetation elevations vary from tidal-based elevations for which SLAMM was developed.

Classification of estuaries is subject to ongoing development by numerous researchers and practitioners. A single, all-encompassing classification system for estuaries in Mediterranean climates with large wave power (e.g. California) has proved elusive. To inform the development of SLAMM and guide its users, we start with an estuarine classification system based on the federal Coastal and Marine Ecological Classification Standard (CMECS) (FGDC, 2012). We follow Heady et al. (2015), who reviewed several estuarine classification systems, and then selected CMECS for their study of California estuaries because of CMECS's national applicability and suitability for fish assessments. The CMECS classification system, as applied to the California (Heady et al., 2015), defines four geomorphic types of estuaries:

- **Embayment** – Defined by land ranging from slight coastal indentations to nearly complete land enclosure. The embayment's hydrology is primarily tidal and saline, but may have significant freshwater influences. Many East Coast estuaries are this type, and hence have been well described by prior versions of SLAMM. Embayments include tidal inlets which are sometime referred to as lagoons in other publications (e.g. Bolinas Lagoon); in this context, the embayment's tidal inlet mouth geometry is controlled by wave-driven sediment transport and tidal exchange much like Lagoonal estuaries.
- **Lagoonal** – Largely enclosed and have reduced exchange with the ocean. This reduced exchange can result in long residence times. These estuaries may be completely closed off from the ocean by a barrier beach, with closures lasting from days, to months, and potentially years. Lagoon estuaries are the most prevalent type of estuary in California (Heady et al., 2015), but are not fully described in prior versions of SLAMM. To aid in updating SLAMM and applying this update version, lagoon estuaries are the primary focus of this document.
- **Riverine** – Often narrower than other types, these estuaries are characterized by relatively high inputs of watershed freshwater flows, with high flushing and a variable salinity range. They are more prevalent in northern California, Oregon and Washington. While improvements to SLAMM made in this version may be applied to Riverine estuaries, much is left to future work.
- **Sound** – A long, narrow waterway that functions as an arm of the ocean. Puget Sound is an archetype and dominates the population of Washington estuaries. However, if Puget Sound is further divided into sub-estuaries where watersheds drain to the Sound, these sub-estuaries can be classified

according to one of the preceding three types. As such, 'sound' might be considered more of super-type. Along with the riverine type, improvements addressing this type are left for future work.

California estuaries exist within a diverse spectrum of estuarine morphology and behavior, varying widely among and within each of the four CMECS classes. Their similarity to one of the four classes may vary at seasonal or inter-annual timescales. In such cases, efforts to select an estuary's type should not be overly constraining or time-consuming. Defining features of CMECS classes within the spectrum are the tidal inlet condition, degree of fluvial input, and the resulting effect on estuarine hydrology. The flexible nature of SLAMM 6.7 works to address this diversity of estuarine morphologies and behavior. Estuarine classification can help but other manners exist to refine parameters important to SLAMM.

Spectrum of Tidal Inlet Conditions and Effects

Estuaries in California span a spectrum of tidal inlet states and water levels, as well as salinity. For this study, we are focused on back-barrier systems. In these systems, the tidal inlet crosses a barrier beach built by wave-driven sediment transport. The estuarine hydrology depends on the power of fluvial discharge and tidal exchange relative to wave power on an average and instantaneous basis, as well as multiple other parameters such as evaporation and wave overtopping. We focus on systems in which the wave-influenced inlet and barrier beach results in estuarine hydrology different than the adjacent ocean, and discretize the tidal inlet spectrum with four categories, hereafter called "subtypes" to distinguish from other classification systems. The four subtypes are: embayment, predominantly open, predominantly closed, and drainage outlet (Behrens et al., 2015). As suggested by their names, open or closed inlet state is a primary characteristic for assigning a lagoon estuary to one of these subtypes. The average annual inlet state substantially alters the hydrology of the lagoon, and subsequently the wetland habitats. The physical processes that interact to determine inlet state are described in a later section.

The lagoon subtypes are listed below from greatest to least tidal connectivity. Greater tidal connectivity is typically associated with lower water levels that are near or within the oceanic tidal range and higher salinity. Less tidal connectivity is associated with higher water levels that may consistently exceed the oceanic tide range and lower salinity. Exceptions are predominantly closed lagoons with relatively high evaporation, resulting in higher-than-ocean salinities and water levels potentially below high tides. These systems are located primarily in central and southern California but are considered indicative of other Mediterranean climates with exposure to relatively powerful waves and sediment. Brief descriptions and example estuaries are provided for each subtype to assist SLAMM users in classifying estuaries that they intend to model with SLAMM.

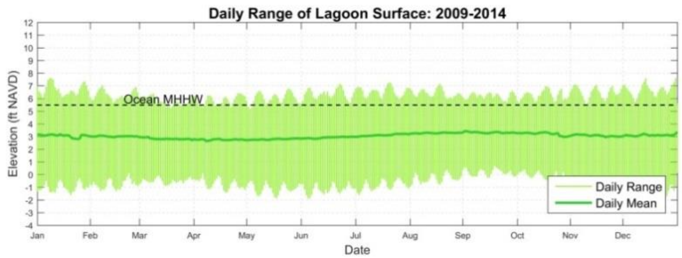
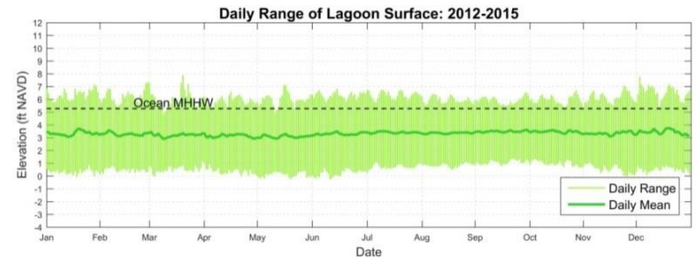
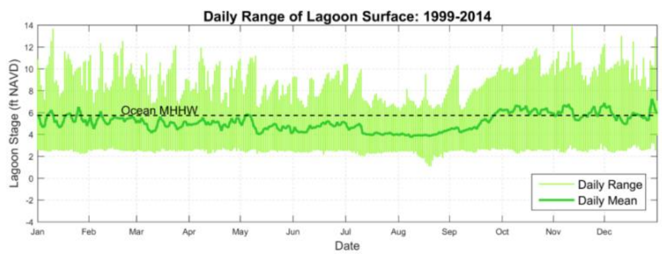
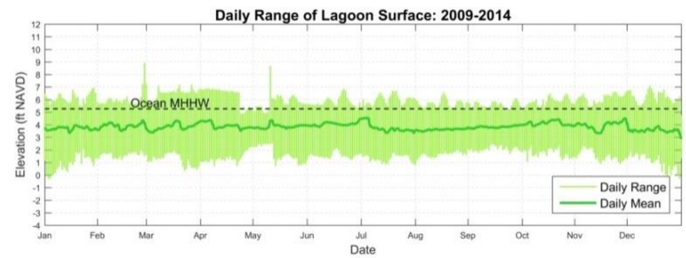
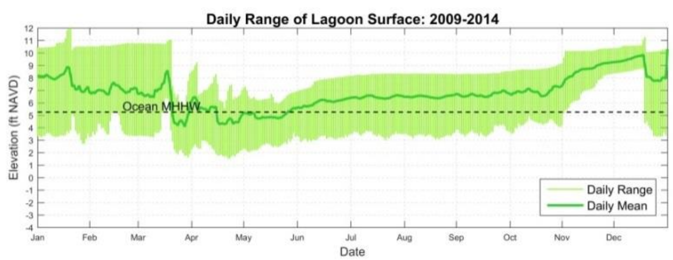
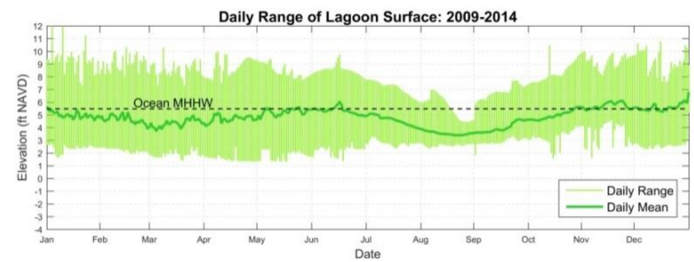
- **Embayment –** Some Embayment estuaries, while not classified under CMECS as lagoons, (because closures are either very infrequent or non-existent) have some characteristics shared by lagoons because of physical processes at their tidal inlet. They typically differ from other embayments in that they are often almost fully enclosed by land and connected to the ocean by only a narrow tidal inlet. The inlet constrains tidal exchange such that the tidal range within the estuary is slightly to significantly less than the oceanic tide range. As another indicator of constrained exchange, the inlet's cross-sectional geometry is likely to evolve at tidal timescales (Goodwin et al., 1996; Williams and Cuff, 1995; Battalio et al., 2006). Although the inlet modulates tidal exchange, the tidal exchange is always or nearly always sufficient to maintain an open inlet. Examples include Elkhorn Slough (PWA 2008) and Bolinas Lagoon (PWA 2006) (locations shown in Figure 10). An oblique aerial of the mouth of Bolinas Lagoon is shown in Figure 11a and representative annual aggregate water level time series are shown in Figure 12a and b.

- **Predominantly open –** These Lagoonal estuaries inhabit the open state for the majority of the year, but are likely to close at least once per year. Closure is often dependent on an increase in wave power that is concurrent with decreased riverine discharge and tidal exchange (e.g. neap tide). Closures typically last between a few weeks to just over month. The location of the Russian River and Goleta Slough, two estuaries of this subtype that were reviewed for this study, are shown in Figure 10. An oblique aerial of the mouth of Russian River (ESA, 2015) is shown in Figure 11b and representative annual aggregate water level time series are shown in Figure 12c and d.
- **Predominantly closed –** These Lagoonal estuaries experience closed inlet lagoon conditions for the majority of the year. Once the hydrologic season favoring closures starts, closure is nearly certain (with conditions described above for closure of "Predominantly Open"). To naturally perturb the estuary from its dominant closed state usually requires a less common event, such as large input of riverine discharge, large wave overtopping event, or intense wave scour. The locations of Santa Ynez River and Carmel River, two estuaries of this subtype that were reviewed for this study, are shown in Figure 10. An oblique aerial of the mouth of the Santa Ynez River is shown in Figure 11c and representative annual aggregate water level time series are shown in Figure 12d and e.
- **Drainage outlet –** This type of lagoon estuary 'drains' in the sense that its bed is generally perched above high tides such that even when the inlet is open, flow is usually one-directional towards the ocean. As such, tidal influence is limited and salinity intrusion is primarily through wave overtopping of the barrier beach. The locations of Scotts Creek and Laguna Creek, two estuaries of this subtype that were reviewed for this study, are shown in Figure 10. An oblique aerial of the mouth of Scotts Creek is shown in Figure 11d and representative annual aggregate water level time series are shown in Figure 12f and g.

Figure 10. Location of selected estuaries.

Figure 11. Representative examples of the four lagoon estuary subtypes.
Aerial images Copyright (C) 2002-2014 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.Californiacoastline.org

Figure 12. Aggregated annual water level observations by lagoon estuary subtype.

<table>
<tr><td>Open tidal</td><td>a) Elkhorn Slough

</td><td>b) Bolinas Lagoon

</td></tr>
<tr><td>Predominantly open</td><td>c) Russian River

</td><td>d) Goleta Slough

</td></tr>
<tr><td>Predominantly closed</td><td>e) Santa Ynez River

</td><td>f) Carmel River

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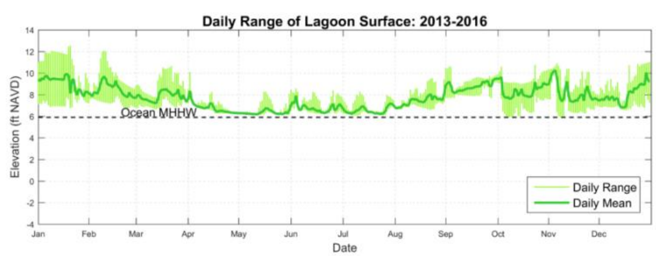
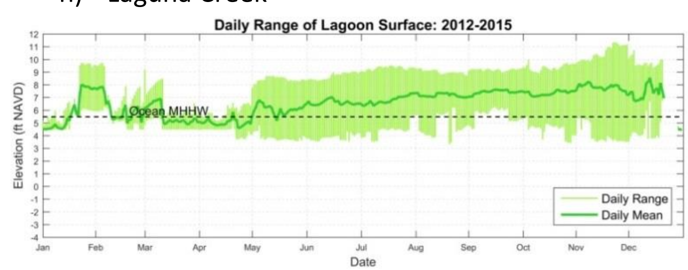
<tr><td>Drainage outlet</td><td>g) Scotts Creek

</td><td>h) Laguna Creek

</td></tr>
</table>

Conceptual Model for California Estuaries

As compared to most embayment estuaries, in which tides freely propagate from the ocean, the hydrology of lagoon estuaries is affected by the inlet's dynamics with the barrier beach. Wave-induced growth of the barrier beach can intrude into the inlet[1], muting or even completely closing the inlet. When the inlet is closed, disconnecting the tides, estuarine water levels becomes a function of inputs (riverine and wave overwash) and exports (groundwater seepage and evaporation). Net inputs raise estuarine water levels above the tide range, resulting in wetland vegetation at higher elevations than tidal ranges. These two processes, inlet dynamics and the estuary water balance, are described below.

Inlet Dynamics

Beaches are built along the ocean shoreline by ocean processes: tidal water levels, waves, and the shoreline's sediment supply (
). This beach-building can create a partial or full barrier across estuarine inlets. Estuaries counter this beach-building by scouring an inlet through the barrier beach with energy derived from tidal exchange, riverine discharge, or a combination of the two (O'Brien, 1969; Johnson, 1973; Battalio et al., 2006).

The balance between beach-building and inlet scour shifts with tides, waves, and riverine discharge. Because these forcing parameters vary continuously, they create dynamic inlet conditions (**Error! Reference source not found.**). These dynamics vary with an estuary's location due to differences in aspect, local tides, wave power, sediment supply, and estuary characteristics. When beach-building overwhelms scour and fills in the inlet, closure occurs.

Closures can be brief, lasting just a few days, or may last for months. A natural end to closure typically occurs when estuarine water levels exceed the barrier beach's crest elevation, causing outflow over the beach that scours a new inlet. In some estuaries, closure is ended artificially by re-excavating the inlet with construction equipment. This artificial breaching aims to lower water levels for flood management or to improve circulation for water quality management.

Inlet dynamics are expressed as inlet geometry that changes at tidal time scales. Inlets migrate laterally to form straight or sinuous channels (
). Under the water surface, inlets' cross sections continuously aggrade or erode. Even at Bolinas Lagoon, an open tidal estuary with no recorded closures, the inlet's cross sectional area has been observed to vary significantly over a single tide cycle (**Error! Reference source not found.**). Similarly, the mouths and channels can migrate, changing lengths and slopes, and extend inland between flood shoals, further complicating measurement and characterization of mouth geometry.

Estuary Water Balance

In lagoon estuaries, water levels are a function of tides, riverine discharge, wave overwash, groundwater seepage, and evaporation (
). When an inlet is open, tides may dominate estuary water levels, with modulation by riverine discharge during high flow events. When beach-building constricts the inlet, the influence of tides becomes muted and the other forces may play a larger role in setting water levels. When an inlet is

[1] The tem "inlet" is used here as a simplification consistent with much of the literature on lagoon estuaries. For "drainage outlets" the mouth is more precisely called an "outlet channel".

closed, tides are blocked from entering the estuary, leaving the other forces to determine the lagoon water balance.

With drainage to the ocean blocked by the barrier beach, riverine discharge accumulates in the estuary, raising water levels. Wave overwash, the result of higher-than average wave conditions, may intermittently contribute ocean water to the estuary. These inflows are offset by outflows.

Figure 13. Lagoon estuary hydrology water balance concept Source: Behrens et al, 2015.

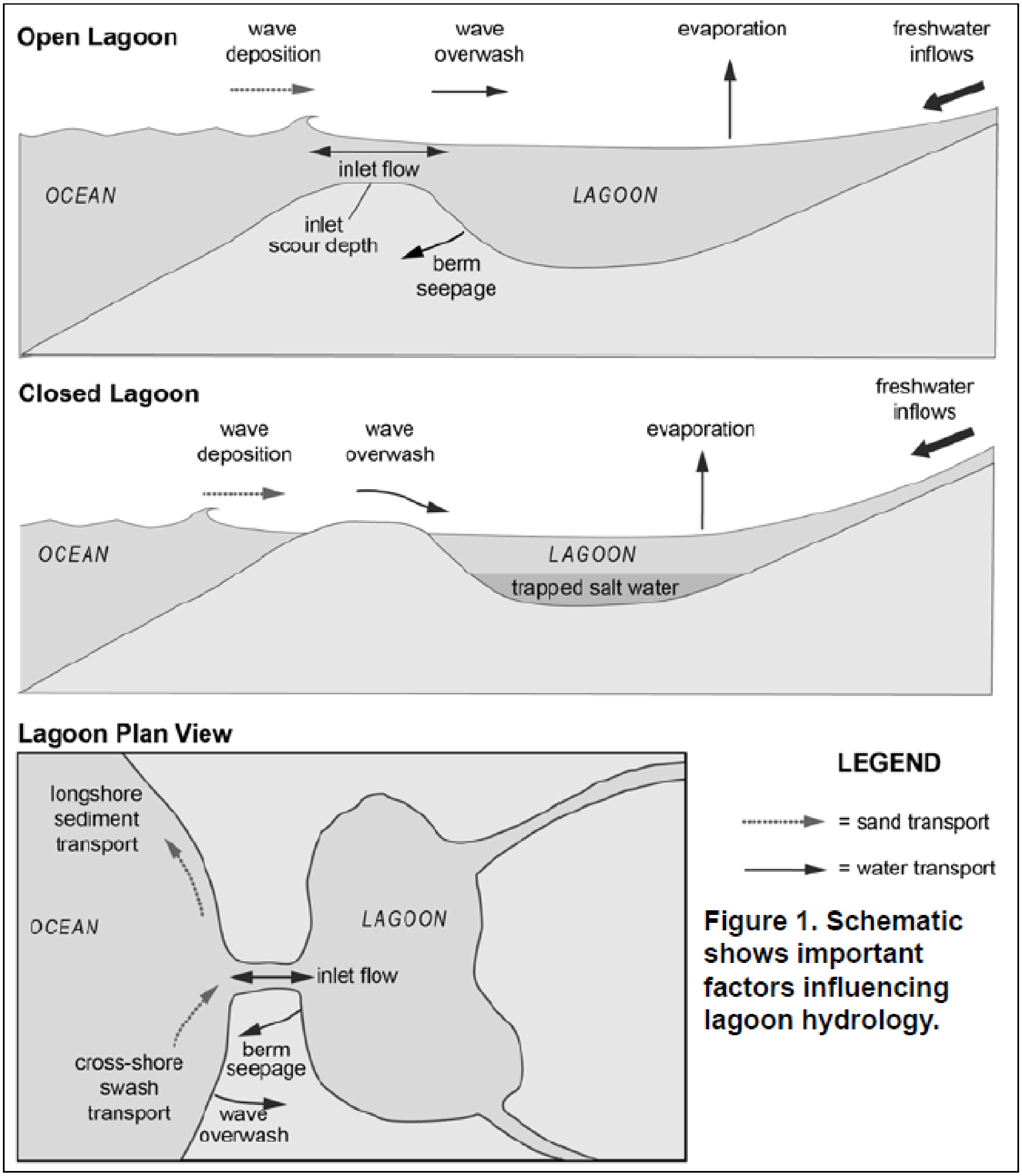


Figure 14. Concept schematic mouth of lagoon estuary (Source: PWA, 2005; Battalio et al, 2007)

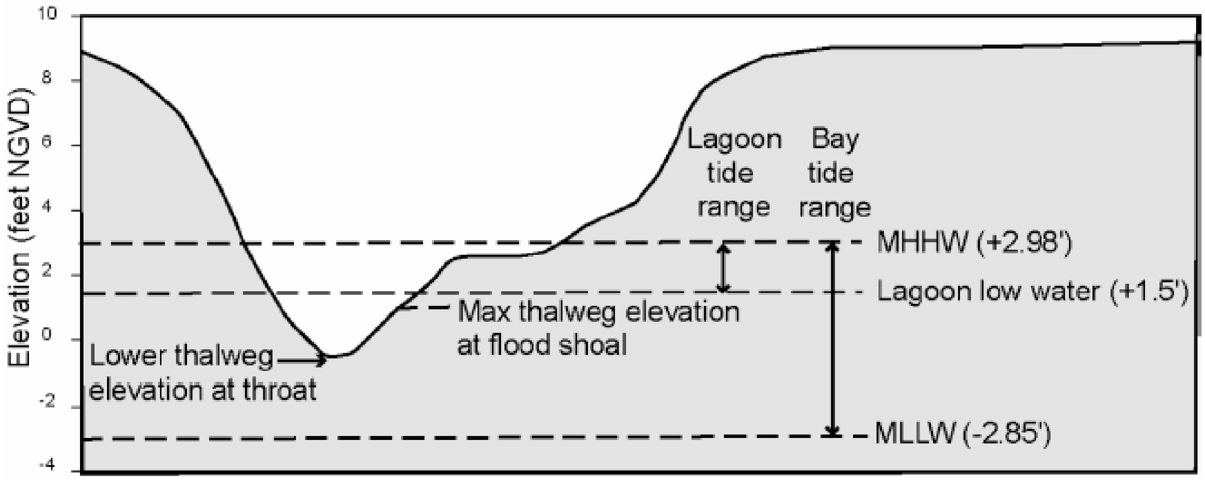
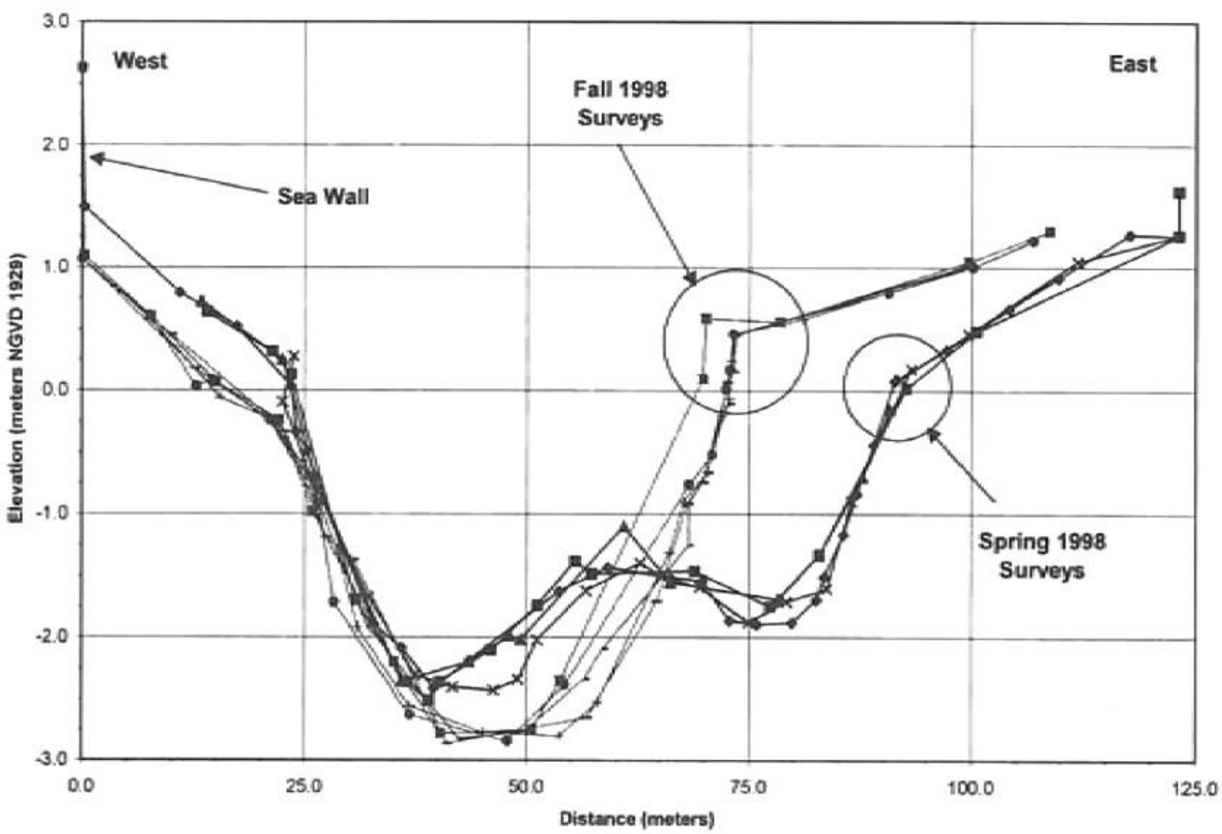


Figure 15. Mouth cross-sections measured at Bolinas Lagoon. Source: DeTemple et al, 1999; PWA, 1998



Groundwater seepage through the barrier beach to the ocean is often the largest outflow component, particularly since the seepage rate increases with increasing estuary water level. Evaporation is typically a smaller component of water leaving the estuary, and may not be significant relative to other components. However, in some southern California estuaries that have a combination of a larger surface area-to-volume ratio, greater solar heating, and lower inflows, evaporation can plan a significant role in the water balance, salinity, and resulting vegetation patterns.

Water volume, as accounted for in the balance, fills the estuary's stage-volume relationship, or hypsometry. This hypsometry, in turn, affects some of the water balance terms: water level provides the gradient for seepage, the surface area affect evaporation. The relative magnitude of discharge, seepage, overwash, and evaporation vary by estuary and also seasonally and instantaneously. The relative magnitudes also affects estuarine subtype; for example, higher discharge tends toward more open conditions. This water balance evolves at an hourly time scale, which has been modeled predictively with a quantified conceptual model to track the water balance and the inlet dynamics (Behrens et al., 2015).

Land-Cover Class Mapping

The lagoon inundation regime is determined in large part by the barrier beach and inlet dynamics. Estuarine wetland land-cover classes are then dependent on the frequency, duration, and depth of inundation. For tidal systems (

), the mouth is open, and vegetation elevations are often related to tide levels as a surrogate for inundation frequency, soil moisture, etc. For systems that close (

), the water levels are often elevated relative to the tides, and available data suggest a range between MHHW and the beach berm crest elevation at each site.

Figure 16 compares probability density functions of lagoon water level and the range of marsh vegetation elevations for eight systems representing the four lagoon subtypes. Closed lagoon water levels, shown in orange, are typically higher and fresher than open-mouth conditions, which are lower and usually brackish or salty. Beach crest elevations are shown for context as these influence lagoon water levels by controlling mouth behavior.

Examples of Open Tidal Lagoon Estuaries

Most fully tidal California Embayment estuaries follow the governing conceptual model of SLAMM, that estuarine land-cover classes are largely determined by ground surface elevations relative to water levels, which can be referenced to oceanic tidal datums (

Figure 17). However, California vegetation species and land-cover classes are different from those found on the East Coast. The definition of California land-cover classes are described above in the section 'California SLAMM simulations'.

A detailed study of tidal hydrology and vegetation in California's Bolinas Lagoon (PWA, 2006) provides high quality hydrologic and land-cover data. The study included observations of water levels, ground surface elevation, and land-cover mapping. The land cover mapping included field observations of vegetation species, which were used to ground truth land-cover mapping from aerial photography. An aerial photograph of the lagoon, overlain with the land-cover classes is shown in

Figure 18. Vegetation species were identified and their elevations tallied relative to both geodetic and tidal vertical datums (

Figure 19). For the more common marsh plant species, the elevation data were extensive enough to plot frequency distributions, as shown for pickleweed, a dominant California tidal marsh species, in Figure 20. Similar distributions for other species are provided in PWA (2006).

Figure 16. lagoon water level probability density function and vegetation elevation.

Open Tidal	Predominantly Open	Predominantly Closed	Drainage Outlet

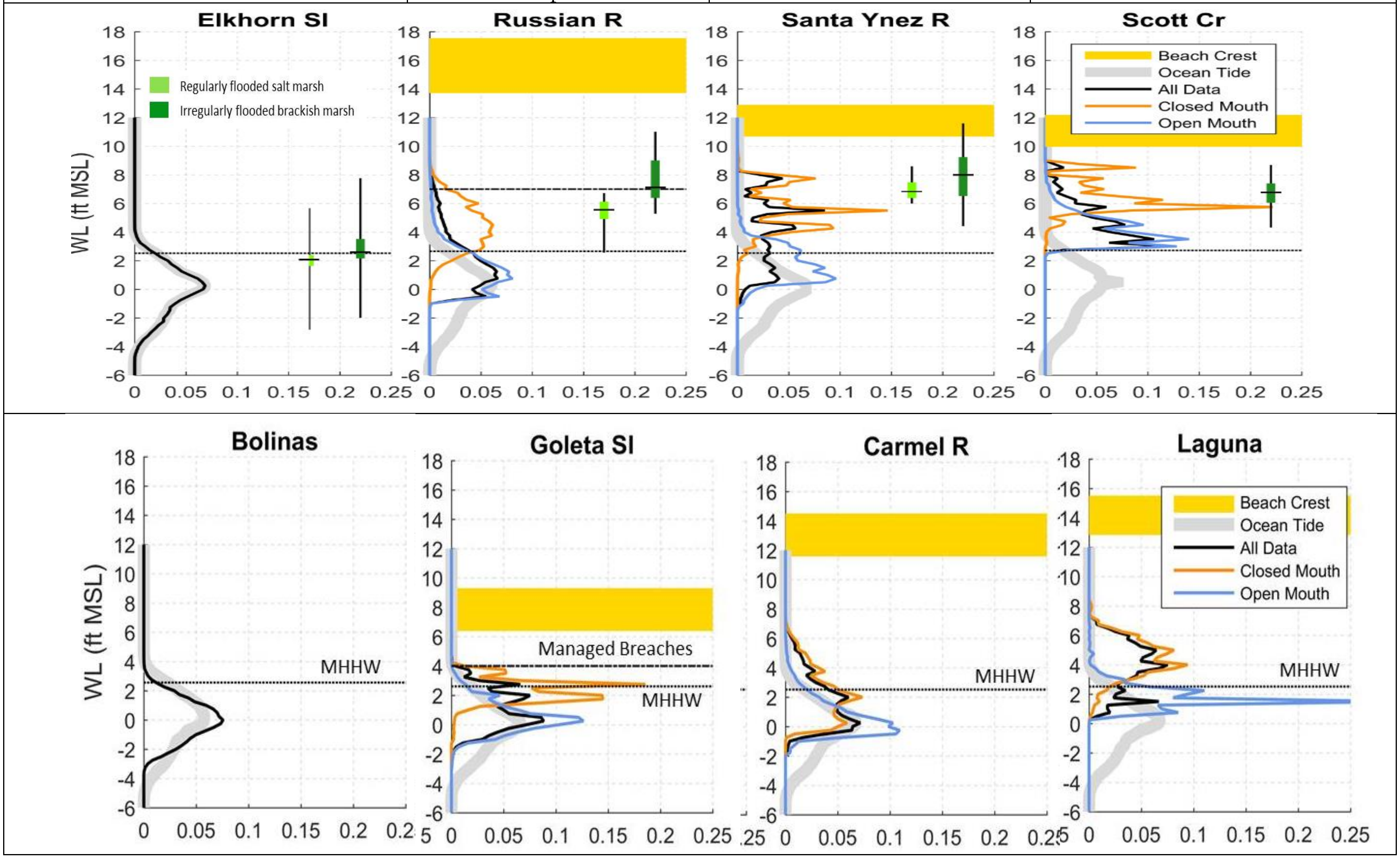


Figure 17. Typical tidal salt marsh elevations relative to tidal datums. Source: PWA (2006)

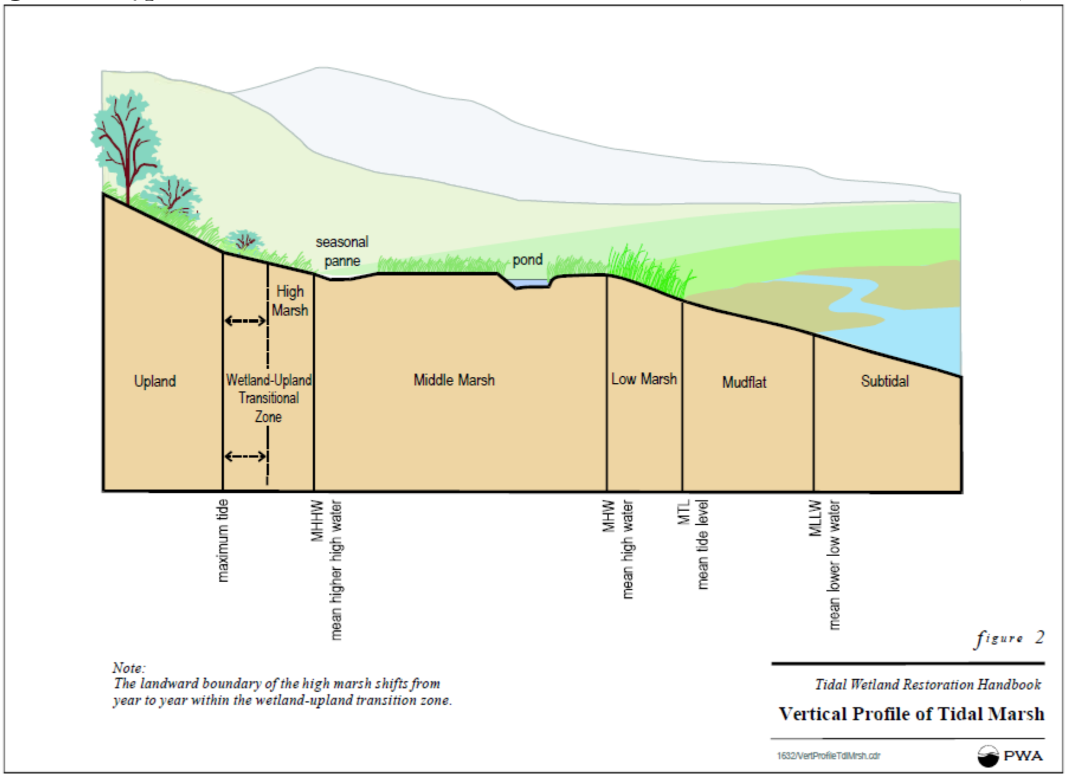


Figure 18. Land-cover classes for Bolinas Lagoon (Source: PWA, 2006)

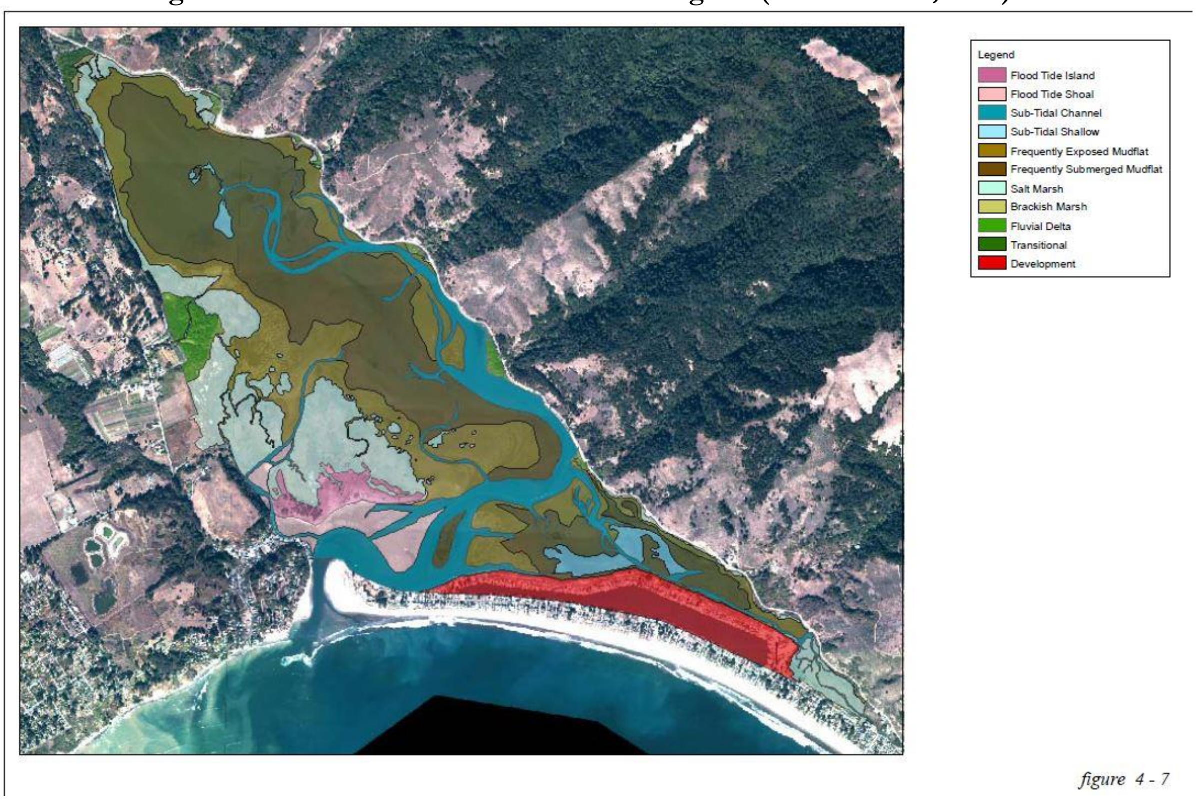


Figure 19. Range of vegetation elevations for Bolinas Lagoon (Source: PWA, 2006)

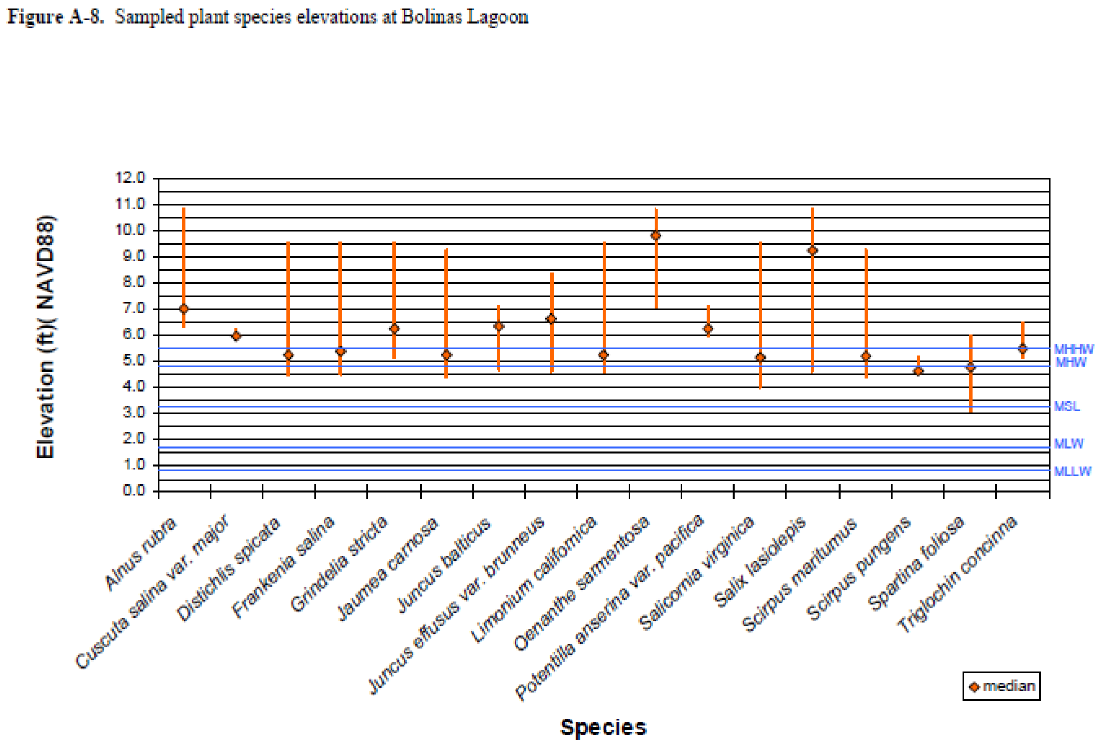
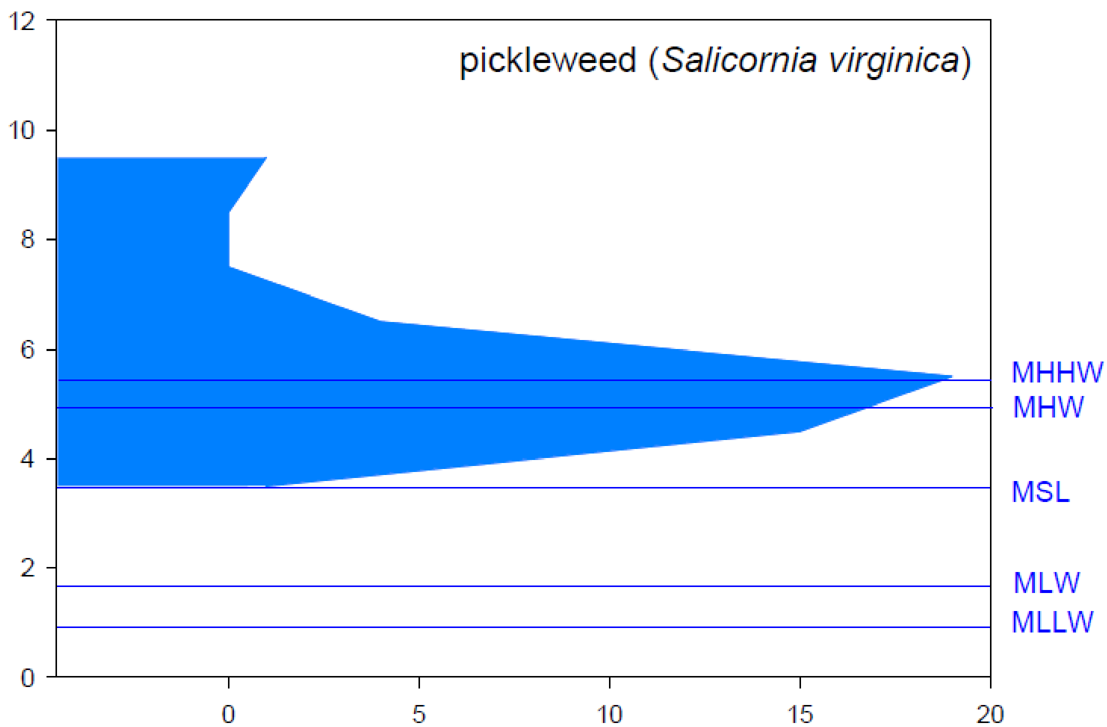


Figure 20. Pickleweed elevation frequency distribution for Bolinas Lagoon (Source: PWA, 2006)



Similar sets of observations have been made at other California embayment estuaries (Appendix A.1 in PWA and Faber, 2004; Van Dyke, 2012). Modeling one or more of these estuaries with the updated version of SLAMM could be a useful validation of the model's land-cover mapping for existing conditions.

Human Interventions and Implications

Most estuaries along California coast are impacted by human activities to some degree, and many are heavily modified. The human interventions range from management activities such as artificial breaching, to watershed changes such as water diversions or excessive sediment yield, to fundamental changes such as hydraulic structures regulating outflows, and filling and diking. Management activities are problematic from a diagnostic perspective, because the actions may vary year-to-year and may not be documented. Therefore, human interventions complicate classification, analysis, and projections of future conditions. Human interventions on the reference sites along with provisional assessments of implications pertinent to this study are follows:

Bolinas Lagoon: The Bolinas Lagoon mouth is a tidal inlet which has been largely "stabilized" by shore armoring of the eastern sand spit (PWA, 2006) (Seadrift Community, visible as "development" in Figure 9). The shore protection and development prevents mouth migration, and also blocks wave overtopping and sand delivery over the spit. Also, the lagoon basin has been directly reduced for development, as well as filled by excessive sediment deposited in the Pine Gulch Creek Delta due to watershed impacts. The implications are a partially stabilized mouth and an incised primary channel, leading to incrementally lower low tides (closer to ocean tides) but slightly reduced high tides.

Elkhorn Slough: The Elkhorn Slough mouth is stabilized by two rock jetties for navigation purposes, and the main channel is constrained by the Highway One crossing. These interventions have converted what was likely a reduced tidal system to a fully tidal system that exports sediment, leading to degradation of marshes (PWA, 2008). Much of the original wetlands were diked and/or drained for agriculture, roads, railroads, or other human uses. We excluded diked areas from this study.

Russian River Estuary: The mouth of the Russian River is mechanically breached to prevent flooding in developed areas along estuary's shoreline (ESA PWA, 2015). A jetty constructed to stabilize the mouth remains in a degraded condition, preventing mouth migration and limiting wave overtopping. The management limits high water while the jetty probably has minor effects mouth state and closure frequency.

Goleta Slough: Goleta Slough was filled to construct a wastewater treatment plant, the Santa Barbara airport, and for agriculture. This changed the system from an open tidal inlet to a predominately closed mouth system. However, because estuarine water levels cause flooding during mouth closure, the mouth is mechanically excavated. Therefore, the hydrology is managed similarly to the natural conditions, with synchronized plant elevations.

Santa Ynez River Estuary: Water diversions from the watershed likely have an effect on breaching frequency and duration, but these effects are not quantified. One roadway crossing resulted in changed hypsometry in the upper reaches of the estuary as the channel downcut and connectivity with the floodplain was degraded. A second crossing lower in the estuary is partially demolished but has trapped sediment and also affected the estuary bathymetry. The implications to estuarine hydrology are likely to be a slight reduction in breaching frequency and duration.

Carmel River Estuary: There are major water diversions for potable water supply, causing the lower reaches of the river, just upstream of the estuary, to "go dry" each summer. This lowers the lagoon water level during the dry season closed-state. This is potentially a major impact to the lagoon hydrology. As shown in Figure 12, water level diversions contribute to the water level dip in the summer. Lagoon water elevations re prevented from getting to high for flood control reasons.

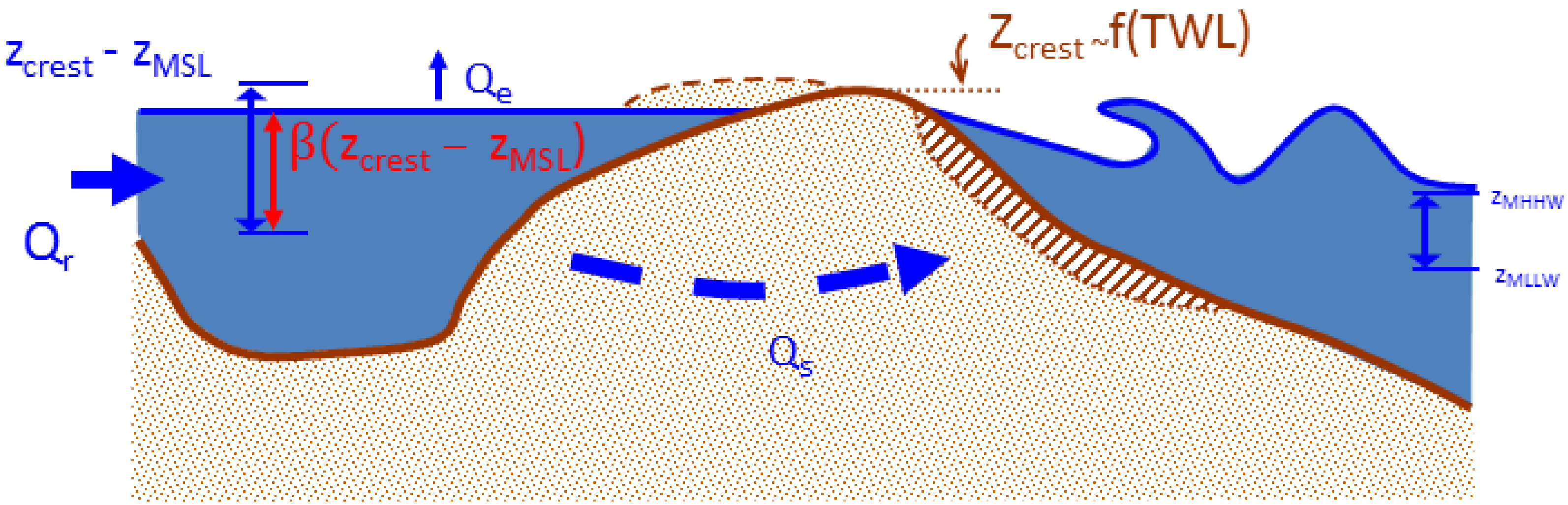
Scott Creek: The Scott Creek Estuary is strongly "stabilized" by the Highway One road crossing and levees (ESA PWA, 2012). The primary implication to natural function is associated with the levees, which impede connectivity between the marsh and the main channel, thereby interfering with the relationship between the channel hydrology and the wetland vegetation. However, several channels have scoured through the berm on the north side, reconnecting with the area from which vegetation elevation data were derived. We used data from several years of water level recorders in the mainstem and throughout the marsh plain to inform hydrologic relationships between the lagoon and marsh plain and resulting vegetation patterns.

Laguna: The Laguna Lagoon was historically impacted by agriculture, and potentially still impacted by water diversions and/or watershed changes. However, this system is the least impacted by humans of the suite of reference systems used in this study.

Implementing Lagoon Conceptual Model in SLAMM

This section describes the process for applying the lagoon conceptual model described above to modeling lagoon estuaries with SLAMM. Figure 21 is a schematic of key terms used to quantify the conceptual model. In this figure, the beach crest (also called berm crest) is a function of ocean total water level (TWL), and is a reference elevation. The distance between the wave-built berm crest and ocean mean sea level (MSL) brackets the elevation of the estuary water level to be used as a vegetation elevation reference. This estuary water level is conceptually similar to the ocean mean sea level used by SLAMM in relation to the "regularly flooded salt marsh" category used by SLAMM and NWI (Figure 16). This reference water level is similar to ocean MSL in terms of its effect on vegetation elevation, via soil moisture and other factors, but is likely higher (perched) above the ocean MSL. A value β is established empirically (or otherwise) to define this estuary references water level, and β is expected to vary between zero and one: A value of zero indicates the reference water level is ocean MSL, implying a fully tidal system that is not perched by the beach barrier, while a value of one indicates a persistently high water level near the beach berm elevation.

Figure 21. Schematic representation of implementing the lagoon conceptual model in SLAMM.



Framing

To frame the implementation of SLAMM for a lagoon estuary, the estuary should first be classified according to lagoon subtype. Brief descriptions and example estuaries are provided above to assist SLAMM users with classification. Observations from the estuary of interest, such as water level data, ground surface elevation, vegetation mapping, and narrative from others familiar with the estuary can inform classification and the subsequent SLAMM modeling. Once classified, the user may refer to previously modeled estuaries of the same subtype for guidance on model setup along with the suggested parameter settings described below.

Representative Water Levels in Lagoon Estuaries

SLAMM's land-cover class mapping is based in large part on the ground surface elevation relative to the regularly-flooded marsh range. SLAMM tracks this inundation range with three water level variables: the "salt elevation" (30-day high water mark), mean higher high water (MHHW) and mean lower low water (MLLW). Based on an initial review of elevation data and vegetation across lagoon subtypes, the effective inundation range in lagoons is shifted upwards relative to oceanic tidal datums previously used in SLAMM As described above, this upwards shift is the result of reduced tidal exchange through a lagoon's tidal inlet or no tidal connectivity across a wave-built barrier through a lagoon's drainage outlet channel[2].

Figure 22 to Figure 24 illustrate the shift in elevation ranges for California SLAMM categories across six lagoon estuaries of different lagoon subtypes[3]. Note in particular how the regularly-flooded and irregularly-flooded marsh elevations are closely correlated with the orange lines (lagoon water range) as opposed to the blue lines (oceanic tide range).

As a first order representation of lagoon conditions, SLAMM's inundation range should be shifted upwards from the elevations set by oceanic tidal datums. To provide a basis for generalizing this upwards shift, the magnitude of the shift is referenced to physical conditions in the estuary. The proposed physical reference points are the barrier beach crest elevation and oceanic mean sea level (MSL). The maximum beach crest elevation represents the upper limit for lagoon inundation; above this elevation, water will spill to the ocean and perhaps scour a new inlet. MSL provides a position relative to tidal datums. The difference between these two elevations serves as a length scale for the upward shift in inundation range above ocean tides. Since the maximum beach crest elevation sets estuary water levels only under extreme conditions, the typical conditions which appear more likely to drive habitat evolution are likely somewhere between MSL and the maximum beach crest or a fraction of the maximum beach crest to MSL difference. This fraction is designated 'β'. As a starting point, until more refined understanding of the relationship between lagoon water levels and land-cover classes are developed, the same upwards shift of $\beta(z_{crest} - z_{MSL})$ can be applied to all three

[2] The channel connecting a lagoon estuary to the mouth is often called a "tidal inlet" but in this study we also use the term "drainage outlet" to describe a creek mouth channel with thalweg above the tide range. This distinction is particularly pertinent when modeling the mouth geometry via hydraulics and sediment transport and to use of applied geomorphology techniques and empirical data.

[3] Figure 22 to Figure 24's box plots show category widths as proportional to wetland acreage. One-meter LiDAR returns were compared against National Wetland Inventory classifications converted into CA SLAMM categories.

of the inundation range parameters (MLLW, MHHW, and the salt boundary), as depicted schematically in

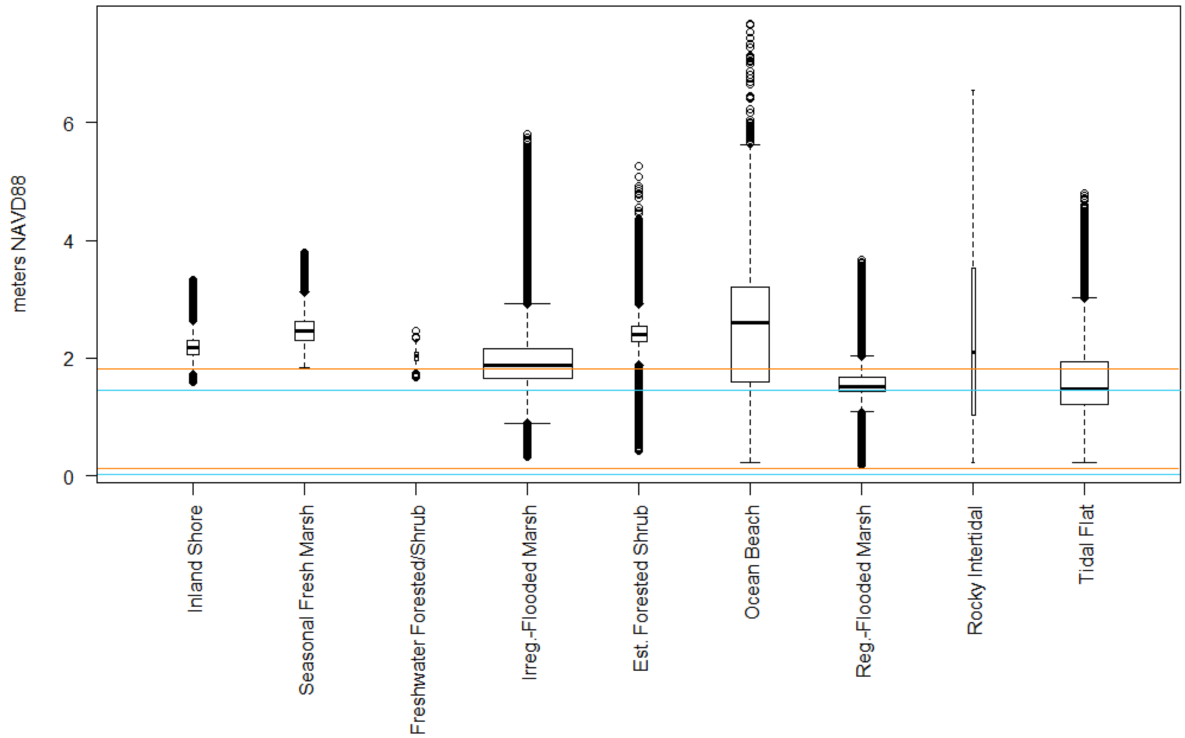
. Alternatively, if the water-level range of the lagoon is known, that range can be specified for the lagoon using the parameter "great diurnal tide (GT) range." (It is acknowledged that when modeling lagoons this parameter is somewhat mislabeled. The "great diurnal tide range" does not apply to lagoonal water levels, but the concept of using a parameter to specify minimum to maximum water levels observed remains appropriate.)

As in the prior version of SLAMM, the inundation range parameters are assumed to progress upwards at the same rate as SLR. In some estuaries, the upward shift in inundation range could alter the inlet dynamics, particularly if the upward shift accesses a larger inundation area, thereby significantly increasing the tidal prism that scours the inlet and altering the frequency of inlet closure. Quantifying the potential influence of this is outside of the scope of the current SLAMM update and left to future work. In advance of future improvements, a user can modify SLAMM's inundation range parameters and elevations at which land-cover classes switch to best replicate observed conditions and anticipate changes with SLR.

This is a simplified version of a more complex conceptual model that requires further development prior to application. The simplified version was applied as a starting point with limited complexity and to provide the broadest application of SLAMM. Although extending this simplified model was beyond the scope of the present study, directions for future work are described below.

Figure 22. Mugu North (top) and Mugu West (bottom) Box Plots

- Box extents are 25th and 75th percentiles
- Whiskers are min and max values within 150% of interquartile range
- Orange lines are approximate lagoonal water extents based on ESA Data
- Blue lines are MLLW and MHHW from NOAA Data
- Diked or tidally-muted areas removed from analysis



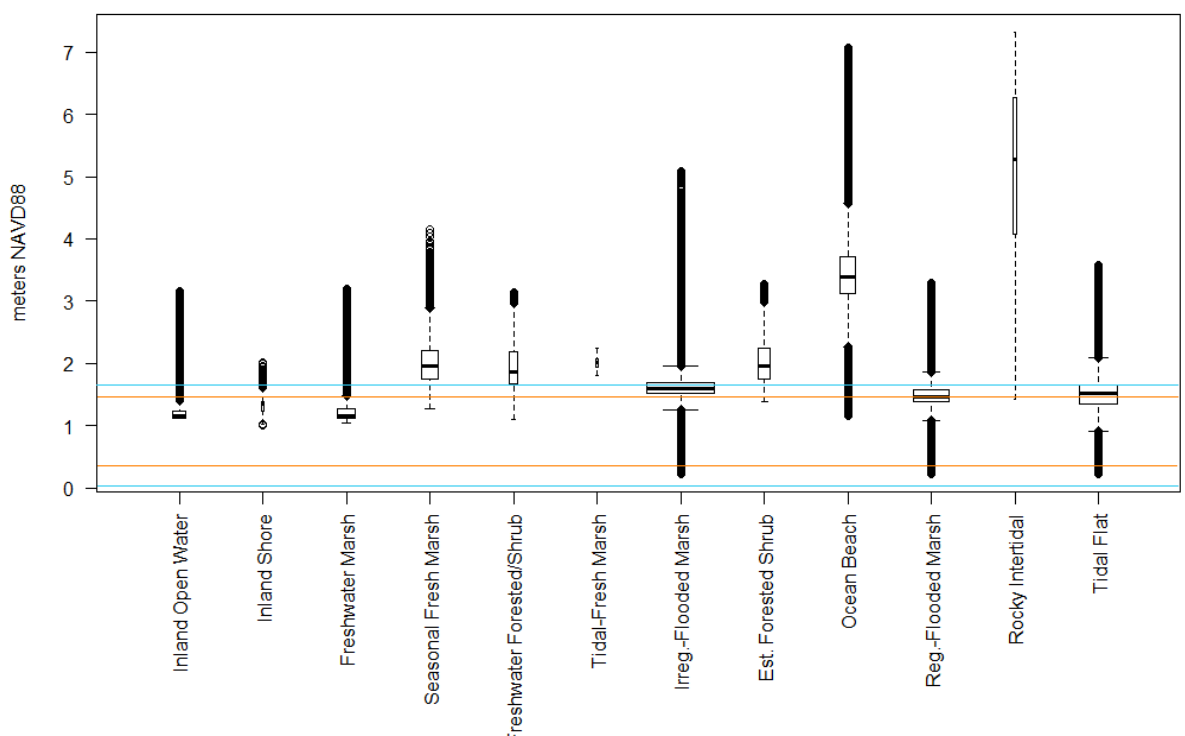
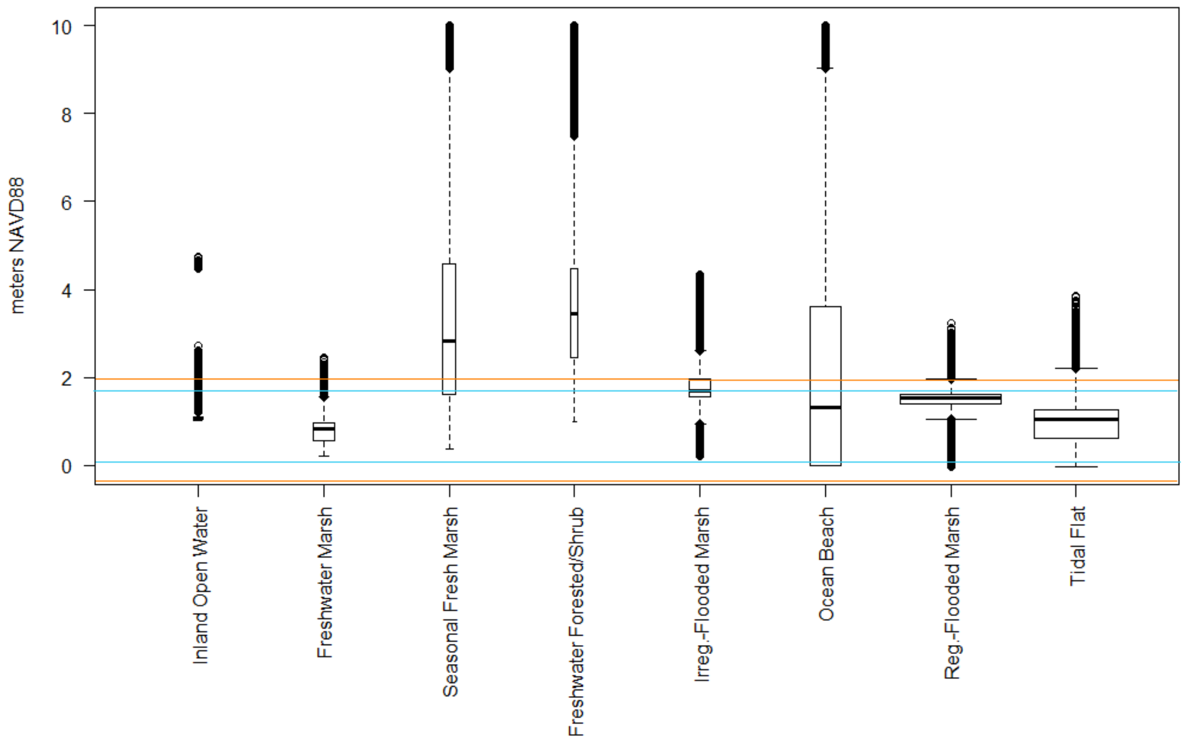


Figure 23. Elkhorn (top) and Russian (bottom) Elevation Box Plots

- Box extents are 25th and 75th percentiles
- Whiskers are min and max values within 150% of interquartile range
- Orange lines are approximate lagoonal water extents based on ESA Data
- Blue lines are MLLW and MHHW from NOAA Data
- Diked or tidally-muted areas removed from analysis



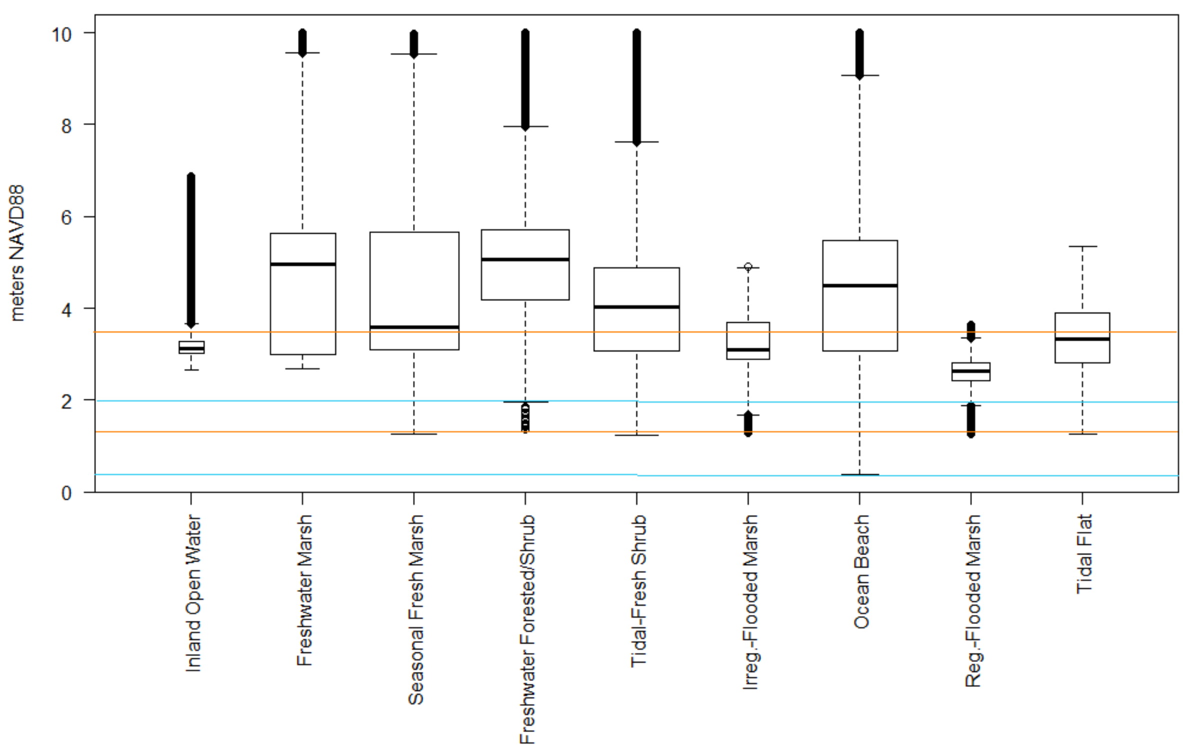
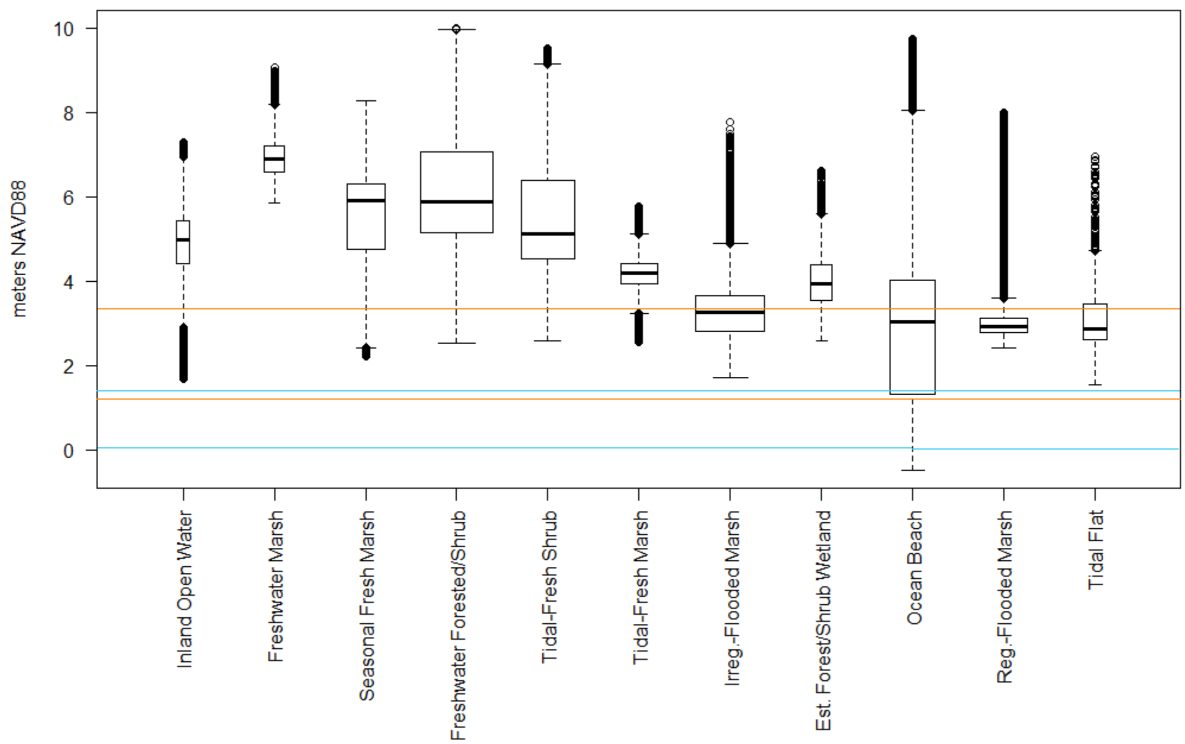
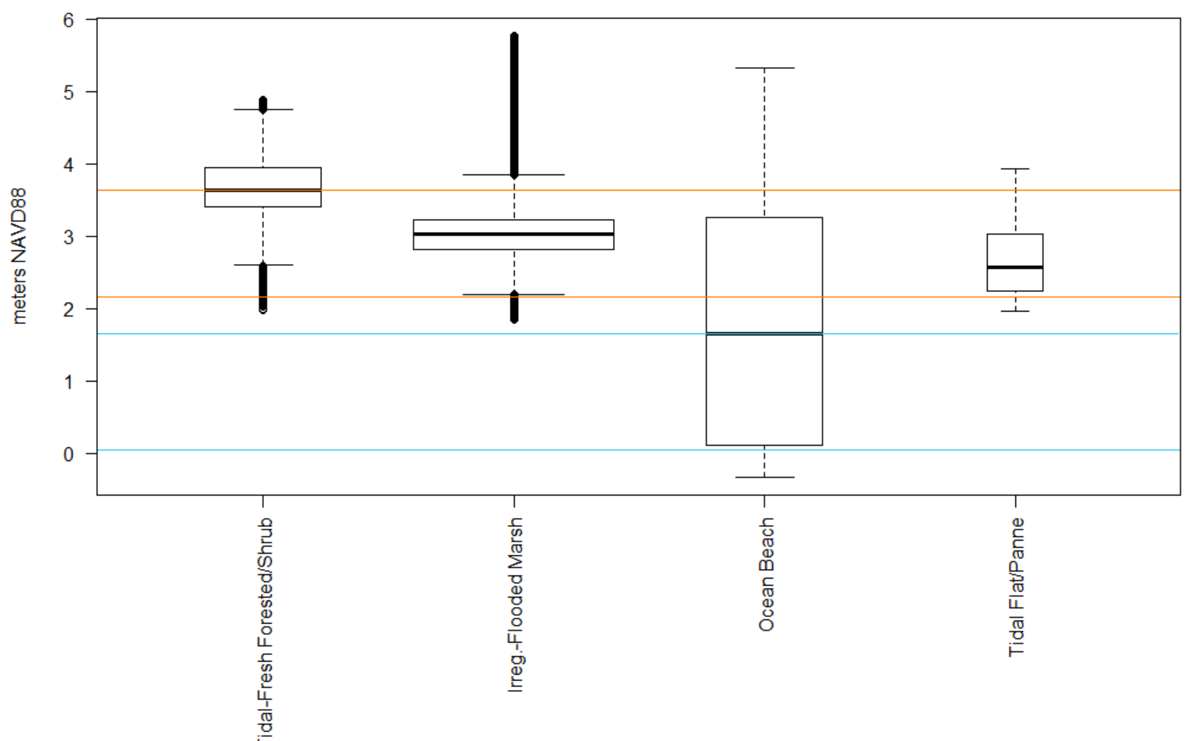


Figure 24. Santa Ynez (top) and Scotts Creek (bottom) Box Plots

- Box extents are 25th and 75th percentiles
- Whiskers are min and max values within 150% of interquartile range
- Orange lines are approximate lagoonal water extents based on ESA Data
- Blue lines are MLLW and MHHW from NOAA Data
- Diked or tidally-muted areas removed from analysis





Parameter Selection

Leveraging the estuary's classification and available data, SLAMM users should select parameters for setting the lagoon inundation range.

MSL can be derived from ocean water level records, which are often available from NOAA if site-specific data is not available. Note that this is the oceanic, not the estuary MSL.

The barrier beach maximum crest elevation can be selected from one or more sources. Observed crest elevations are most direct, but would need to be collected enough through space and time to sufficiently resolve temporal variability. Elevations surveyed in the fall are most appropriate, when low-steepness, low to moderate power "constructive" waves have built the beach berm elevation upward. If oceanic wave data are available, these data can be combined with tidal water level to predict total water levels, which describe the extent of wave runup. Since wave runup is the building processes for the barrier beach, the upper range of wave runup (e.g. the 2% exceedance probability) can be a surrogate for the maximum beach crest elevation. Finally, if site-specific data are not available, the user can select a berm crest elevation based on similar reference locations where this information is available.

The fraction of the difference between the maximum beach crest elevation and MSL, β, can be selected from reference estuaries for which this parameter is estimated. Table 5 summarizes the typical range of β, based on our current understanding.

Table 5. Typical range for β based on lagoon subtype.

Lagoon Subtype	Typical range for β
Open tidal	0-0.1
Predominantly open	0.1-0.3
Predominantly closed	0.2-0.4
Drainage outlet	0.2-0.5

A second alternative, or in addition, the user may record water levels in the estuary and develop distributions similar to those in

Figure 16 and Figure 20. These water level distributions can be related to the NWI vegetation classes of regularly-flooded marsh and irregularly-flooded marsh as shown in

Figure 16. With long enough data sets, the annual water surface elevation plots may also be used to characterize the estuary and identify its subtype.

Since applications of this approach are limited, and each estuary will have its own characteristics (including management practices), users will probably need to adjust these parameters as part of an iterative calibration process that seeks to optimize the relationship between SLAMM's mapping of existing land-cover classes and known land- cover classes. By engaging in this testing process with the broader SLAMM community, users can assist with the generalization of these parameters, to aid in the development of templates to guide other users.

Future Extensions of Conceptual Model and SLAMM

The scope of this first phase of a framework to broadly improving SLAMM for California estuaries focused on establishing California lagoons. Since the improved model has not yet been tested across a range of lagoon estuaries, we anticipate that best practices for implementation, as well as understanding of model parameterization will continue to evolve. The overall goal is to continue to improve SLAMM's generalization so it can be more accurately applied for California estuaries with limited *a priori* data.

For example, we have focused on the upward shift of inundation levels above the tides behind a wave-built barrier. A second order effect is the change in the distribution of plant elevations about this lifted elevation. For example, low tides are typically reduced and the vertical extent of emergent saltwater plants may be compressed. However, predominately closed and drainage outlet systems may have expanded vertical extremes that persist long enough to expand the vertical range of plants. Salinity is an important parameter that could be used as a characteristic in a more advanced conceptual framework. In the prior example of predominately closed systems, high evaporation can reduce water levels and increase salinity. Also, low salinity systems have different elevation relationships which also vary more with latitude along the California of the United States.

Below is an initial list of future extensions of the work to improve SLAMM for California estuaries:

- Water level parameters
    - Lagoonal water levels may not move on a one-to-one basis with sea-level rise. We plan to add flexibility to this relationship.
    - We also plan to add a "maximum" lagoon water-level parameter to examine cases where lagoons will not likely be allowed to flood lands behind them in the advent of SLR.
    - Lagoon water levels may need alternative inundation-range variables to inform land-cover mapping instead of the standard SLAMM "30-day," "MHHW," and "MLLW" variables.
    - We will examine the potential compression of inundation that can occur in lagoon estuaries, especially predominantly closed (Figure 12e and f) or drainage outlet (Figure 12g and h) subtypes.
- Vegetation land-cover classes
    - Compression of the inundation range will correspondingly affect the inundation duration. Wetland plant species have different inundation tolerances, so may respond differently to this phenomenon.
- Salinity
    - Our conceptual model does not explicitly account for salinity, unless linkage to an external salinity model is included within model setup. Salinity may vary dramatically through space and time within and among estuary subtypes. The inundation and duration of saline water likely have a stronger affect on vegetation classes than the inundation and duration of freshwater. Explicitly accounting for this difference may refine results.
- Pacific Northwest estuaries
    - Estuaries in this region are often of the riverine type, a type not considered in detail for this initial phase. Further examination of this type will be undertaken especially considering salinity relationships with SLR and river mile.

    - Pacific Northwest estuaries host tidal swamp habitats, which need special consideration in terms of relationships with salinity, inundation, and duration of inundation, as well as habitat generation time.
- Shift in inlet dynamics
    - In some estuaries, an upward shift in inundation range could alter inlet dynamics. This is particularly true if the upward shift produces a larger inundation area, thereby significantly increasing the tidal prism that scours the inlet and alters the frequency of inlet closure. The potential influence of such a shift can be explored with the quantified conceptual model (QCM) that combines an estuary water balance with inlet channel dynamics (Behrens et al. 2015). The QCM can first be used to explore the potential magnitude of this shift, and then, if warranted, be coupled with SLAMM.

Uncertainty Analysis

SLAMM includes a Monte-Carlo uncertainty-analysis module to provide confidence statistics for model results as a function of input uncertainties and errors. This capability can be accessed through the "Uncertainty / Sensitivity Setup" button on the "Execute" screen.

A user may specify uncertainty distributions for nearly all input variables, including tide ranges, erosion rates, accretion rates, the strength of accretion feedbacks to SLR, and the rate of sea-level rise by 2100. Changes in most parameters are specified using "multipliers" to existing parameter values. This enables a single distribution to represent uncertainty over many input subsites simultaneously. Depending on the specific variable and the amount of available information, any one of several distributions may be appropriate. The interface supports normal, lognormal, triangular, and uniform distributions. The user selects a distribution and provides key parameters (e.g. mean, standard deviation, max, min, most likely value, etc.) to characterize it.

The effect of input parameter uncertainty on the predicted wetland response is generated by running multiple SLAMM simulations with different input parameter values sampled from their uncertainty distributions. After the user enters the total number of simulated scenarios to be run, efficient sampling from the distributions is obtained with the Latin Hypercube method (McKay et al., 1979).

The effects of errors in elevation data inputs and spatial datum-corrections can also be independently or simultaneously assessed. To evaluate these errors, a spatially autocorrelated error field is added to the existing digital elevation map (or datum correction) in the manner of Heuvelink (1998). This approach uses the normal distribution as specified by the RMSE for the dataset and applies it randomly over the entire study area, but with spatial autocorrelation included. Adding spatial autocorrelation to the elevation errors accounts for the likely spatial clustering of measurement errors (Hunter and Goodchild 1997). This method provides a means to calculate a number of equally-likely elevation maps given error statistics about the data set. A stochastic analysis may then be run (running the model with each of these elevation maps) to assess the overall effects of elevation (or vertical-datum-correction) uncertainty. Heuvelink's method has been widely recommended as an approach for assessing the effects of elevation data uncertainty (Darnell et al.

2008; Hunter and Goodchild 1997). It is recommended that the user assume that elevation errors are strongly spatially autocorrelated, using a “p-value” of 0.2495, for example.

For each simulated scenario results are produced as standard SLAMM outputs: Word/GIF maps, ASCII rasters, and tables of results that can then be further processed and analyzed. A summary of uncertainty statistics is also automatically produced.

Sensitivity Analysis

“Sensitivity” refers to the variation in output of a mathematical model with respect to changes in the values of the model inputs (Saltelli 2001). It provides a ranking of the model input assumptions with respect to their relative contribution to model output variability or uncertainty (U.S. Environmental Protection Agency 1997).

SLAMM 6 includes a built-in nominal range sensitivity analysis (Frey and Patil 2001), which may be used to examine the sensitivity of multiple model outputs to multiple model input parameters. This capability can be accessed through the "Uncertainty / Sensitivity Setup" button on the "Execute" screen. The user first selects which model parameters to vary. When executed, the model iteratively steps through each of the parameters and varies them by a specified percent in the positive and negative direction and saves model results in an Excel file.

A *sensitivity statistic* may then be calculated such that when a 10% change in the parameter results in a 10% change in the model result, the sensitivity is calculated as 100%.

Definitions and Acronyms

Definitions

SLAMM 6 Definitions used within the decision tree:

- "Adjacent to Ocean": Is the cell within 500 m of open ocean (in off-shore direction)
- "Adjacent to Water": Is the cell within 500 m of water (incl. fresh, looking off-shore)?
- "Adjacent to Salt": Is the cell within 500 m of salt water or salt marsh? (looking off-shore)
- "Adjacent to Estuarine Forested/Shrub Wetland": Is the cell within 500 m of the Estuarine Forested/Shrub category (California model only).
- "All Wetland": Cell is at least 90% wetlands categories;
- "Near Water": Is there water within 6 km of the off-shore direction or to lee?
- "Near Salt": Is there salt-water or salt marsh within 6 km of the off-shore direction?
- "Tropical": Does the site have mangroves present (>0.5% of site map)

General Definitions:

- Mean Tide Level: (MTL) Datum located midway between MHHW and MLLW.
- Mean Higher High Water: (MHHW) Mean of the higher high water height each day.
- Mean Lower Low Water (MLLW): Mean of the lower low water height each day.
- Great Diurnal Tide Range (GT): Difference between MHHW and MLLW.

Acronyms

DEM	Digital Elevation Model
HTU	Half Tide Unit
IPCC	Intergovernmental Panel on Climate Change
GT	Great Diurnal Tide Range
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
MTL	Mean Tide Level
NAVD 88	The North American Vertical Datum of 1988
NWI	National Wetlands Inventory, from US Fish and Wildlife Service
SLAMM	Sea Level Affecting Marshes Model

Technical Details

Installing SLAMM

The SLAMM 6.7 Installer may be downloaded from the following site:

TBA

The interface can be used to open SLAMM6 files or SLAMM6 (or SLAMM text files) may be dragged and dropped onto the SLAMM6 interface. Also, SLAMM6 files or text files may be passed to the executable as a parameter and they will be automatically opened up upon execution.

Source Code

The open source code may be accessed by going through the "About" screen within SLAMM or alternatively may be directly downloaded here:

http://warrenpinnacle.com/prof/SLAMM6/SLAMM6.7_Open_Source.zip

This code requires Delphi XE3 or later to compile.

Command Line Option

To automatically run a SLAMM simulation, save an existing SLAMM6 file as "txt" rather than the "SLAMM6" file-type. Examination of that file will show hundreds of parameters, hopefully labeled in a relatively self-evident manner. You can pass that file-name as a parameter to the executable and the file will be loaded upon startup or the simulation will be run.

To run the simulation automatically and terminate the application on completion you must change the very last line of that file to "ExecuteImmediately: True". This enables the use of a DOS batch file such as the following:

```
C:
cd "\Program Files\SLAMM6"
pause
SLAMM6.exe "c:\SLAMM\Data\VA.SLAMM6.txt"
SLAMM6.exe "c:\SLAMM\Data\NC.SLAMM6.txt"
echo Your runs are complete.
pause
```

Input File Requirements

SLAMM 6 accepts the following types of data for each cell modeled (raster format)

- Slope Data: Slope of each cell, used to calculate partial changes in cell composition. As derived from the Digital Elevation Map. (units are degrees)
- DEM Data: Digital Elevation Map data. Preferrable derived from LiDAR. Contour data (from the National Elevation Database, for example) are typically inappropriate to use for calculating sea level rise effects but serve as data in areas where more precise data are not available (in this case the elevation preprocessor module may be used). (units are meters)
- NWI Data: National Wetlands Inventory categories. Dominant wetland category for each cell is converted into SLAMM categories. This is also used to refine elevation estimates for each cell. Table 4 provides the crosswalk information for Cowardin codes to SLAMM categories
- Dike Data: Boolean defining whether each cell is protected by dikes or not. This is available as an attribute of the NWI data, special modifier "h."
- IMP Data: Percent impervious raster, derived from National Land Cover Dataset. Dry land with percent impervious greater than 25% is assumed to be "developed dry land."

For sites within the USA, parameters for tidal ranges, and the NAVD88 correction may be downloaded from the NOAA CO-OPS database.

Erosion rates should be based on site-specific data whenever possible. Default erosion rates are 2.0 meters per year for marshes, 1.0 meters per year for swamps, and 0.5 meters per year for tidal flats, based on a combination of professional judgment and a brief literature survey. Note, for all wetland classes except for tidal flats, these erosion rates presume that the wave-action threshold for erosion (editable for marshes, and 9km for swamps) has been exceeded prior to the incidence of horizontal erosion.

Producing Data Files

Raster files should have units of meters, be delivered in space delimited format with carriage returns following each row of cells (Standard ArcGIS or ArcView with Spatial Analyst output, see the last page of this document). SLAMM model output will also be provided in the ASCII Raster format as shown below. This can then be easily imported into whatever GIS platform is being used for producing final graphics for the NWF report. SLAMM outputs are compatible with MapWindow GIS, ArcGIS or ArcView with Spatial Analyst.

Digital elevation map data must first be processed to obtain raster coverage for slope and elevation.

Using Spatial Analyst's tools, slope can be derived from this data set in units of "degrees." *(Note, depending on the software used, this slope may only be accurate if both your x,y horizontal units and your elevation units (z units) are of the same type (e.g., all feet or all meters). If they are in different units, which is often the case, the Derive Slope function will give you inaccurate results. Therefore, converting to UTM units first may make the most sense.)*

Next, the NWI data must be transformed into a grid that matches the DEM (NED) grid as produced above. One procedure for this conversion is listed below:

- Extract NWI polygons unless you have a current coverage already available. NWI data are publicly available at http://www.nwi.fws.gov/
- Add an additional numeric field to the NWI database (attached to the shape file) that will contain the relevant SLAMM category.
- Use a lookup table with Excel or a database program of your choice to assign SLAMM categories to each NWI polygon. Note: The technician will need to make sure that each NWI polygon code in the database extraction is included in the lookup table and fill in any missing assignments using Table 4 (See NWI to SLAMM Category Conversion section)
- Convert the NWI polygons to a grid with the same cell size, cell count, and boundaries as the NED grid.
- Export the NWI raster to the ASCII RASTER format showing SLAMM5 categories.
- Units for the projection and "cell-size" should be meters.

If it is desirable to model the protective effects of dikes, an additional raster layer must be specified that indicates whether each cell is protected by dikes or not. This can be derived from NWI special modifier "h=Diked/Impounded." As noted above, in the section on Levee and Dike inputs, this raster can also be set up to specify dike locations and elevations, or a combination of the two dike-modeling options may be used.

The processing of GIS data for use by SLAMM is not an insignificant task that requires moderately advanced GIS skills and up-to-date GIS software. This work will likely require ArcView Spatial Analyst and/or the use of scripting languages to complete.

Output Data

Each time a model is executed a "run-record" file is output into the same directory as the "SLAMM6" file. This file includes information about the time and date the model is run, the parameters that were utilized, and the dates of external data files used to drive the model. Furthermore, all output files produced are enumerated with file dates and their locations are listed within this file. This new option enables a user to clearly understand which model parameters are associated with which set of results, and also to easily understand the difference between two different model runs. For more information on using the "run-record file, see the *SLAMM 6.7 Users Manual.*

NWI to SLAMM Category Conversion

The tables provided below may not provide a perfect linkage between the Cowardin classification system (as utilized by NWI) and SLAMM land-cover classes. However, they provide a good starting point. Professional judgment and site-specific factors should always be taken into consideration when examining resulting SLAMM land-cover maps. Elevation analysis can also be instructive. It must be acknowledged that Bill Wilen the former head of the National Wetlands Inventory spent many hours carefully vetting and refining the crosswalk presented in Table 6.

Please note that an Excel database containing conversions between NWI classes and SLAMM land-cover classes is included as part of the SLAMM installation package (it is located in the same directory as the SLAMM executable is installed).

An alternative California-specific NWI-to-SLAMM conversion is provided in Appendix A. For the California SLAMM extension, researchers carefully considered several wetland classification systems within the study area. Maps of National Wetland Inventory (NWI), CALVEG, Elkhorn NERR, and a previous SLAMM application for Mugu Lagoon data were rendered and compared to satellite imagery and local site-specific knowledge. Ultimately National Wetland Inventory data were chosen as the basis for wetland maps in this project for the following reasons:

- NWI codes are ubiquitous across the entirety of the West Coast;
- NWI horizontal accuracy was deemed similar to CALVEG (or better for some estuaries);
- NWI is used as the habitat input for SLAMM on the east coast, the NWI-SLAMM crosswalk for east coast wetlands received extensive expert validation which were leveraged here;
- NWI codes more closely match the new set of West-Coast SLAMM categories coded into the model.

The California crosswalk was vetted and refined by the project's technical advisory committee and potential end users. However, site-specific knowledge or data should be utilized whenever possible to refine habitat classification and boundaries.

The way that the model now codes categories as objects is a significant step towards allowing landscape categories to be flexible and editable within its interface. The only significant remaining step is to add a graphical-user-interface allowing category characteristics to be modified.

Table 6: NWI Classes to SLAMM 6 Categories ("Traditional" SLAMM Categories)

		NWI code characters					
SLAMM Code	Name	System	Subsystem	Class	Subclass	Water Regime	Notes
1	Developed Dry Land (upland)	U					SLAMM assumes developed land will be defended against sea-level rise. Categories 1 & 2 need to be distinguished manually.
2	Undeveloped Dry land (upland)	U					
3	Nontidal Swamp	P	NA	FO, SS	1, 3 to 7, None	A,B,C,E,F,G,H,J,K None or U	Palustrine Forested and Scrub-Shrub (living or dead)
4	Cypress Swamp	P	NA	FO, SS	2	A,B,C,E,F,G,H,J,K None or U	Needle-leaved Deciduous forest and Scrub-Shrub (living or dead)
5	Inland Fresh Marsh	P	NA	EM, **f ****	All None	A,B,C,E,F,G,H,J,K None or U	Palustrine Emergents; Lacustrine and Riverine Nonpersistent Emergents
		L	2	EM	2 None	E, F, G, H, K None or U	
		R	2, 3	EM	2 None	E, F, G, H, K None or U	
6	Tidal Fresh Marsh	R	1	EM	2, None	Fresh Tidal N, T	Riverine and Palustrine Freshwater Tidal Emergents
		P	NA	EM	All, None	Fresh Tidal S, R, T	
7	Transitional Marsh / Scrub Shrub	E	2	SS, FO	1, 2, 4 to 7,None	Tidal M, N, P None or U	Estuarine Intertidal, Scrub-shrub and Forested (ALL except 3 subclass)
8	Regularly Flooded Marsh (Saltmarsh)	E	2	EM	1 None	Tidal N None or U	Only regularly flooded tidal marsh No intermittently flooded "P" water Regime
9	Mangrove **Tropical settings only, otherwise 7**	E	2	FO, SS	3	Tidal M, N, P None or U	Estuarine Intertidal Forested and Scrub-shrub, Broad-leaved Evergreen
10	Estuarine Beach old code BB and FL = US	E	2	US	1,2 Important codes	Tidal N, P	Estuarine Intertidal Unconsolidated Shores
		E	**2**	**US**	**None**	**Tidal N, P**	**Only when shores (need images or base map)**
11	Tidal Flat old code BB and FL =US	E	2	US	3,4 None	Tidal M, N None or U	Estuarine Intertidal Unconsolidated Shore (mud or organic) and Aquatic Bed; Marine Intertidal Aquatic Bed
		E	2	AB	All Except 1	Tidal M, N None or U	
		E	**2**	**AB**	**1**	**P**	**Specifically, for wind driven tides on the south coast of TX**
		M	2	AB	1, 3 None	Tidal M, N None or U	
12	Ocean Beach old code BB and FL = US	M	2	US	1,2 Important	Tidal N, P	Marine Intertidal Unconsolidated Shore, cobble-gravel, sand
		M	2	US	None	Tidal P	
13	Ocean Flat old code BB and FL = US	M	2	US	3,4 None	Tidal M, N None or U	Marine Intertidal Unconsolidated Shore, mud or organic, (low energy coastline)

Source, Bill Wilen, National Wetlands Inventory.

Also see the Excel database of NWI Codes to SLAMM Categories installed with the SLAMM 6 Installer in the directory with the SLAMM 6 Executable.

Table 6 (cont.): NWI Classes to SLAMM 6 Categories

		NWI code characters					
SLAMM Code	Name	System	Subsystem	Class	Subclass	Water Regime	Notes
14	Rocky Intertidal	M	2	RS	All None	Tidal M, N, P None or U	Marine and Estuarine Intertidal Rocky Shore and Reef
		E	2	RS	All None	Tidal M ,N, P None or U	
		E	2	RF	2, 3 None	Tidal M, N, P None or U	
		E	2	AB	1	Tidal M, N None or U	
15	Inland Open Water old code OW = UB	R	2	UB, AB	All, None	All, None	Riverine, Lacustrine, and Palustrine Unconsolidated Bottom, and Aquatic Beds
		R	3	UB, AB, RB	All, None	All, None	
		L	1, 2	UB, AB, RB	All, None	All, None	
		P	NA	UB, AB, RB	All, None	All, None	
		R	5	UB	All	Only U	
16	Riverine Tidal Open Water old code OW = UB	R	1	All **Except EM**	All None **Except 2**	Fresh Tidal S, R, T, V	Riverine Tidal Open water **R1EM2 falls under SLAMM Category 6**
17	Estuarine Open Water (no h* for diked / impounded) old code OW=UB	E	1	All	All None	Tidal L, M, N, P	Estuarine subtidal
18	Tidal Creek	E	2	SB	All, None	Tidal M, N, P Fresh Tidal R, S	Estuarine Intertidal Streambed
19	Open Ocean old code OW = UB	M	1	All	All	Tidal L, M, N, P	Marine Subtidal and Marine Intertidal Aquatic Bed and Reef
		M	2	RF	1,3, None	Tidal M, N, P None or U	
20	Irregularly Flooded Marsh	E	2	EM	1, 5 None	P	Irregularly Flooded Estuarine Intertidal Emergent marsh
		E	**2**	**US**	**2, 3, 4 None**	**P**	**Only when these salt pans are associated with E2EMN or P**
21	Not Used						
22	Inland Shore old code BB and FL = US	L	2	US, RS	All	All Nontidal	Shoreline not pre-processed using Tidal Range Elevations
		P	NA	US	All, None	All Nontidal None or U	
		R	2, 3	US, RS	All, None	All Nontidal None or U	
		R	4	SB	All, None	All Nontidal None or U	
23	Tidal Swamp	P	NA	SS, FO	All, None	Fresh Tidal R, S, T	Tidally influenced swamp

* **h=Diked/Impounded** - When it is desirable to model the protective effects of dikes, an additional raster layer must be specified.

** Farmed wetlands are coded Pf
All: valid components
None: no Subclass or Water regime listed
U: Unknown water regime
NA: Not applicable

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Water Regimes	
Nontidal	A, B, C, E, F,G, J, K
Saltwater Tidal	L, M, N, P
Fresh Tidal	R, S,T, V

Note: Illegal codes must be categorize by intent.
Old codes BB, FL = US
Old Code OW = UB

Source, Bill Wilen, National Wetlands Inventory

For more information on the NWI coding system see Appendix A of Dahl et al 2009.

Example of ASCII input for the SLAMM model as produced by Spatial Analyst / ArcGIS:

```
ncols         325
nrows         467
xllcorner     423260
yllcorner     5149750
cellsize      30
NODATA_value  -9999
17 17 17 17 17 17 17 17 17 17 17 17 17 17 17 17 17 17 17 17
17 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11
11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11
11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 11 2
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11 11 11 11 11 11 11 11 11 17 11 11 11 11 11 11 11 11 8 8 8 8
8 8 11 11 11 8 11 8 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2
2 2 2 2 8 11 8 2 2 2 2 2 2 2 2 2 2 2 2 2 8 8 8 8 8 17 17 11 8
8 8 8 8 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 7 7 7 2
2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 -9999 -9999 -
9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -9999 -
9999 . . .
```

(Note: “cellsize” unit must be meters)

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Appendix A: California SLAMM Categories to NWI Crosswalk

GIS Num	SLAMM California	NWI
103	Agriculture	Pf
104	Aritificial Pond	L1UBKh
104	Aritificial Pond	L1UBKr
104	Aritificial Pond	L1UBKx
104	Aritificial Pond	L2UBKh
104	Aritificial Pond	L2UBKx
104	Aritificial Pond	PABKr
104	Aritificial Pond	PABKrx
104	Aritificial Pond	PABKx
104	Aritificial Pond	PUSKCx
104	Aritificial Pond	PUSKh
104	Aritificial Pond	PUSKx
105	Artificial Salt Pond	L2UBK1h
105	Artificial Salt Pond	L2UBK3h
105	Artificial Salt Pond	L2USK1h
105	Artificial Salt Pond	L2USK1x
105	Artificial Salt Pond	L2USK3h
105	Artificial Salt Pond	L2USKh
105	Artificial Salt Pond	L2USKx
105	Artificial Salt Pond	PUSK1h
106	Inland Open Water	L1ABH
106	Inland Open Water	L1UBH
106	Inland Open Water	L1UBHh
106	Inland Open Water	L1UBHx
106	Inland Open Water	L1UBV
106	Inland Open Water	L1UBVh
106	Inland Open Water	L2AB3H
106	Inland Open Water	L2AB3Hx
106	Inland Open Water	L2ABH
106	Inland Open Water	L2ABHh
106	Inland Open Water	L2UBF
106	Inland Open Water	L2UBFh
106	Inland Open Water	L2UBFx
106	Inland Open Water	L2UBH
106	Inland Open Water	L2UBH3h
106	Inland Open Water	L2UBHh
106	Inland Open Water	L2UBHx

GIS Num	SLAMM California	NWI
106	Inland Open Water	PAB/UBHh
106	Inland Open Water	PAB3/UBHx
106	Inland Open Water	PAB3F
106	Inland Open Water	PAB3Fh
106	Inland Open Water	PAB3Fx
106	Inland Open Water	PAB3G
106	Inland Open Water	PAB3H
106	Inland Open Water	PAB3Hh
106	Inland Open Water	PAB3Hx
106	Inland Open Water	PAB4F
106	Inland Open Water	PAB4Fx
106	Inland Open Water	PAB4H
106	Inland Open Water	PAB4Hh
106	Inland Open Water	PAB4Hx
106	Inland Open Water	PABC
106	Inland Open Water	PABF
106	Inland Open Water	PABFh
106	Inland Open Water	PABFx
106	Inland Open Water	PABG
106	Inland Open Water	PABH
106	Inland Open Water	PABHh
106	Inland Open Water	PABHx
106	Inland Open Water	PABV
106	Inland Open Water	PUB/ABFh
106	Inland Open Water	PUB/ABHh
106	Inland Open Water	PUB3F
106	Inland Open Water	PUB3G
106	Inland Open Water	PUB3H
106	Inland Open Water	PUBF
106	Inland Open Water	PUBFh
106	Inland Open Water	PUBFr
106	Inland Open Water	PUBFx
106	Inland Open Water	PUBH
106	Inland Open Water	PUBH3h
106	Inland Open Water	PUBH3x
106	Inland Open Water	PUBHh
106	Inland Open Water	PUBHr

GIS Num	SLAMM California	NWI
106	Inland Open Water	PUBHx
106	Inland Open Water	PUBK
106	Inland Open Water	PUBK1h
106	Inland Open Water	PUBK1x
106	Inland Open Water	PUBKh
106	Inland Open Water	PUBKHx
106	Inland Open Water	PUBKr
106	Inland Open Water	PUBKrx
106	Inland Open Water	PUBKx
106	Inland Open Water	PUBT
106	Inland Open Water	PUBV
106	Inland Open Water	PUBVx
106	Inland Open Water	PUSR
106	Inland Open Water	PUSS
106	Inland Open Water	PUSSh
107	Inland Shore	L2RSCh
107	Inland Shore	L2UB3H
107	Inland Shore	L2USAh
107	Inland Shore	L2USAx
107	Inland Shore	L2USC
107	Inland Shore	L2USC3h
107	Inland Shore	L2USCh
107	Inland Shore	PUS
107	Inland Shore	PUS/FOA
107	Inland Shore	PUS/SSA
107	Inland Shore	PUS/SSC
107	Inland Shore	PUSA
107	Inland Shore	PUSAh
107	Inland Shore	PUSAr
107	Inland Shore	PUSAx
107	Inland Shore	PUSC
107	Inland Shore	PUSC1x
107	Inland Shore	PUSC3h
107	Inland Shore	PUSCh
107	Inland Shore	PUSChx
107	Inland Shore	PUSCr
107	Inland Shore	PUSCx
108	Freshwater Marsh	PAB/EMFh
108	Freshwater Marsh	PAB/EMHh
108	Freshwater Marsh	PAB/EMHx

GIS Num	SLAMM California	NWI
108	Freshwater Marsh	PEM/ABFh
108	Freshwater Marsh	PEM/ABHx
108	Freshwater Marsh	PEM/SSF
108	Freshwater Marsh	PEM/SSFh
108	Freshwater Marsh	PEM/UBFx
108	Freshwater Marsh	PEM/UBH
108	Freshwater Marsh	PEM/UBV
108	Freshwater Marsh	PEM1/UBF
108	Freshwater Marsh	PEM1/UBH
108	Freshwater Marsh	PEM1/UBHx
108	Freshwater Marsh	PEM1F
108	Freshwater Marsh	PEM1Fh
108	Freshwater Marsh	PEM1Fx
108	Freshwater Marsh	PEM1G
108	Freshwater Marsh	PEM1H
108	Freshwater Marsh	PEM1Hh
108	Freshwater Marsh	PEM1Kh
108	Freshwater Marsh	PEM1Kx
108	Freshwater Marsh	PEMF
108	Freshwater Marsh	PEMFd
108	Freshwater Marsh	PEMFh
108	Freshwater Marsh	PEMFx
108	Freshwater Marsh	PEMH
108	Freshwater Marsh	PEMHh
108	Freshwater Marsh	PEMHx
108	Freshwater Marsh	PEMKFx
108	Freshwater Marsh	PEMKh
108	Freshwater Marsh	PEMKx
108	Freshwater Marsh	PEMN
108	Freshwater Marsh	PEMV
108	Freshwater Marsh	PUB/EMF
108	Freshwater Marsh	PUB/EMH
108	Freshwater Marsh	PUB/EMHx
108	Freshwater Marsh	R2EMF
108	Freshwater Marsh	R2EMHx
109	Seasonal Freshwater Marsh	L2EM2Ch
109	Seasonal Freshwater Marsh	L2EMAh
109	Seasonal Freshwater Marsh	L2EMCh
109	Seasonal Freshwater Marsh	PAB/EMCx
109	Seasonal Freshwater Marsh	PEM/ABCx

GIS Num	SLAMM California	NWI
109	Seasonal Freshwater Marsh	PEM/FOA
109	Seasonal Freshwater Marsh	PEM/FOC
109	Seasonal Freshwater Marsh	PEM/FOCx
109	Seasonal Freshwater Marsh	PEM/SS1A
109	Seasonal Freshwater Marsh	PEM/SS1C
109	Seasonal Freshwater Marsh	PEM/SSA
109	Seasonal Freshwater Marsh	PEM/SSAh
109	Seasonal Freshwater Marsh	PEM/SSAx
109	Seasonal Freshwater Marsh	PEM/SSB
109	Seasonal Freshwater Marsh	PEM/SSC
109	Seasonal Freshwater Marsh	PEM/SSCh
109	Seasonal Freshwater Marsh	PEM/SSCx
109	Seasonal Freshwater Marsh	PEM/USA
109	Seasonal Freshwater Marsh	PEM/USAh
109	Seasonal Freshwater Marsh	PEM/USAx
109	Seasonal Freshwater Marsh	PEM/USC
109	Seasonal Freshwater Marsh	PEM/USCh
109	Seasonal Freshwater Marsh	PEM/USCx
109	Seasonal Freshwater Marsh	PEM1/FO1A
109	Seasonal Freshwater Marsh	PEM1/SS1B
109	Seasonal Freshwater Marsh	PEM1/SS1C
109	Seasonal Freshwater Marsh	PEM1/SS1Ch
109	Seasonal Freshwater Marsh	PEM1/USAh
109	Seasonal Freshwater Marsh	PEM1A
109	Seasonal Freshwater Marsh	PEM1Ad
109	Seasonal Freshwater Marsh	PEM1Af
109	Seasonal Freshwater Marsh	PEM1Ah
109	Seasonal Freshwater Marsh	PEM1Ai
109	Seasonal Freshwater Marsh	PEM1Ax
109	Seasonal Freshwater Marsh	PEM1B
109	Seasonal Freshwater Marsh	PEM1Bd
109	Seasonal Freshwater Marsh	PEM1Bh
109	Seasonal Freshwater Marsh	PEM1C
109	Seasonal Freshwater Marsh	PEM1Cd
109	Seasonal Freshwater Marsh	PEM1Cf
109	Seasonal Freshwater Marsh	PEM1Ch
109	Seasonal Freshwater Marsh	PEM1Ci
109	Seasonal Freshwater Marsh	PEM1Cs
109	Seasonal Freshwater Marsh	PEM1Cx
109	Seasonal Freshwater Marsh	PEM1D

GIS Num	SLAMM California	NWI
109	Seasonal Freshwater Marsh	PEM1E
109	Seasonal Freshwater Marsh	PEM1J
109	Seasonal Freshwater Marsh	PEM1R
109	Seasonal Freshwater Marsh	PEM1Rh
109	Seasonal Freshwater Marsh	PEMA
109	Seasonal Freshwater Marsh	PEMAd
109	Seasonal Freshwater Marsh	PEMAh
109	Seasonal Freshwater Marsh	PEMAs
109	Seasonal Freshwater Marsh	PEMAx
109	Seasonal Freshwater Marsh	PEMB
109	Seasonal Freshwater Marsh	PEMBh
109	Seasonal Freshwater Marsh	PEMBx
109	Seasonal Freshwater Marsh	PEMC
109	Seasonal Freshwater Marsh	PEMCd
109	Seasonal Freshwater Marsh	PEMCh
109	Seasonal Freshwater Marsh	PEMCr
109	Seasonal Freshwater Marsh	PEMCrx
109	Seasonal Freshwater Marsh	PEMCs
109	Seasonal Freshwater Marsh	PEMCx
109	Seasonal Freshwater Marsh	PEMJ
109	Seasonal Freshwater Marsh	PUS/EMA
109	Seasonal Freshwater Marsh	PUS/EMAh
109	Seasonal Freshwater Marsh	PUS/EMAx
109	Seasonal Freshwater Marsh	PUS/EMC
109	Seasonal Freshwater Marsh	PUS/EMCh
109	Seasonal Freshwater Marsh	PUS/EMCx
109	Seasonal Freshwater Marsh	R2EMC
110	Seasonally Flooded Agriculture	PEMAf
110	Seasonally Flooded Agriculture	PEMBf
110	Seasonally Flooded Agriculture	PEMCf
112	Freshwater Forested/Shrub	PEM1/FO4B
112	Freshwater Forested/Shrub	PEM1/FO4C
112	Freshwater Forested/Shrub	PEM1/FO5B
112	Freshwater Forested/Shrub	PFO
112	Freshwater Forested/Shrub	PFO/EM1C
112	Freshwater Forested/Shrub	PFO/EMA
112	Freshwater Forested/Shrub	PFO/EMB
112	Freshwater Forested/Shrub	PFO/EMC
112	Freshwater Forested/Shrub	PFO/EMCx
112	Freshwater Forested/Shrub	PFO/SSA

GIS Num	SLAMM California	NWI
112	Freshwater Forested/Shrub	PFO/SSAh
112	Freshwater Forested/Shrub	PFO/SSAx
112	Freshwater Forested/Shrub	PFO/SSC
112	Freshwater Forested/Shrub	PFO/SSCh
112	Freshwater Forested/Shrub	PFO/SSCx
112	Freshwater Forested/Shrub	PFO/SSF
112	Freshwater Forested/Shrub	PFO/SSJ
112	Freshwater Forested/Shrub	PFO/USC
112	Freshwater Forested/Shrub	PFO1/4A
112	Freshwater Forested/Shrub	PFO1/4C
112	Freshwater Forested/Shrub	PFO1/EM1A
112	Freshwater Forested/Shrub	PFO1/EM1F
112	Freshwater Forested/Shrub	PFO1/SS1A
112	Freshwater Forested/Shrub	PFO1/SS1C
112	Freshwater Forested/Shrub	PFO1A
112	Freshwater Forested/Shrub	PFO1Ah
112	Freshwater Forested/Shrub	PFO1Ax
112	Freshwater Forested/Shrub	PFO1B
112	Freshwater Forested/Shrub	PFO1C
112	Freshwater Forested/Shrub	PFO1Ch
112	Freshwater Forested/Shrub	PFO1Cx
112	Freshwater Forested/Shrub	PFO1F
112	Freshwater Forested/Shrub	PFO1Fh
112	Freshwater Forested/Shrub	PFO4/1A
112	Freshwater Forested/Shrub	PFO4/1C
112	Freshwater Forested/Shrub	PFO4A
112	Freshwater Forested/Shrub	PFO4B
112	Freshwater Forested/Shrub	PFO4C
112	Freshwater Forested/Shrub	PFO5C
112	Freshwater Forested/Shrub	PFOA
112	Freshwater Forested/Shrub	PFOAd
112	Freshwater Forested/Shrub	PFOAh
112	Freshwater Forested/Shrub	PFOAx
112	Freshwater Forested/Shrub	PFOB
112	Freshwater Forested/Shrub	PFOC
112	Freshwater Forested/Shrub	PFOCh
112	Freshwater Forested/Shrub	PFOCx
112	Freshwater Forested/Shrub	PFOF
112	Freshwater Forested/Shrub	PFOH
112	Freshwater Forested/Shrub	PFOJ

GIS Num	SLAMM California	NWI
112	Freshwater Forested/Shrub	PSS/EM1C
112	Freshwater Forested/Shrub	PSS/EMA
112	Freshwater Forested/Shrub	PSS/EMAh
112	Freshwater Forested/Shrub	PSS/EMB
112	Freshwater Forested/Shrub	PSS/EMC
112	Freshwater Forested/Shrub	PSS/EMCh
112	Freshwater Forested/Shrub	PSS/EMCx
112	Freshwater Forested/Shrub	PSS/EMF
112	Freshwater Forested/Shrub	PSS/EMJ
112	Freshwater Forested/Shrub	PSS/FOA
112	Freshwater Forested/Shrub	PSS/FOB
112	Freshwater Forested/Shrub	PSS/FOC
112	Freshwater Forested/Shrub	PSS/FOCh
112	Freshwater Forested/Shrub	PSS/FOCx
112	Freshwater Forested/Shrub	PSS/FOF
112	Freshwater Forested/Shrub	PSS/USA
112	Freshwater Forested/Shrub	PSS/USAh
112	Freshwater Forested/Shrub	PSS/USC
112	Freshwater Forested/Shrub	PSS1/EM1A
112	Freshwater Forested/Shrub	PSS1/EM1B
112	Freshwater Forested/Shrub	PSS1/EM1C
112	Freshwater Forested/Shrub	PSS1/EM1F
112	Freshwater Forested/Shrub	PSS1/FO1C
112	Freshwater Forested/Shrub	PSS1/UBF
112	Freshwater Forested/Shrub	PSS1/USA
112	Freshwater Forested/Shrub	PSS1/USC
112	Freshwater Forested/Shrub	PSS1A
112	Freshwater Forested/Shrub	PSS1Ah
112	Freshwater Forested/Shrub	PSS1B
112	Freshwater Forested/Shrub	PSS1Bh
112	Freshwater Forested/Shrub	PSS1C
112	Freshwater Forested/Shrub	PSS1Cd
112	Freshwater Forested/Shrub	PSS1Ch
112	Freshwater Forested/Shrub	PSS1Cx
112	Freshwater Forested/Shrub	PSS1D
112	Freshwater Forested/Shrub	PSS1F
112	Freshwater Forested/Shrub	PSS1Fh
112	Freshwater Forested/Shrub	PSS1H
112	Freshwater Forested/Shrub	PSS1Hh
112	Freshwater Forested/Shrub	PSS1J

GIS Num	SLAMM California	NWI
112	Freshwater Forested/Shrub	PSS4/FO4B
112	Freshwater Forested/Shrub	PSS4B
112	Freshwater Forested/Shrub	PSSA
112	Freshwater Forested/Shrub	PSSAd
112	Freshwater Forested/Shrub	PSSAh
112	Freshwater Forested/Shrub	PSSAx
112	Freshwater Forested/Shrub	PSSB
112	Freshwater Forested/Shrub	PSSC
112	Freshwater Forested/Shrub	PSSCd
112	Freshwater Forested/Shrub	PSSCh
112	Freshwater Forested/Shrub	PSSCx
112	Freshwater Forested/Shrub	PSSF
112	Freshwater Forested/Shrub	PSSFh
112	Freshwater Forested/Shrub	PSSJ
112	Freshwater Forested/Shrub	PSSKx
113	Tidal Freshwater Forested/Shrub	PFO/SSR
113	Tidal Freshwater Forested/Shrub	PFO/SSS
113	Tidal Freshwater Forested/Shrub	PFO1R
113	Tidal Freshwater Forested/Shrub	PFO1S
113	Tidal Freshwater Forested/Shrub	PFOR
113	Tidal Freshwater Forested/Shrub	PFORh
113	Tidal Freshwater Forested/Shrub	PFOS
113	Tidal Freshwater Forested/Shrub	PFOSx
113	Tidal Freshwater Forested/Shrub	PSS/EMR
113	Tidal Freshwater Forested/Shrub	PSS/EMS
113	Tidal Freshwater Forested/Shrub	PSS/FOR
113	Tidal Freshwater Forested/Shrub	PSS/USR
113	Tidal Freshwater Forested/Shrub	PSS1R
113	Tidal Freshwater Forested/Shrub	PSS1S
113	Tidal Freshwater Forested/Shrub	PSSR
113	Tidal Freshwater Forested/Shrub	PSSRh
113	Tidal Freshwater Forested/Shrub	PSSRx
113	Tidal Freshwater Forested/Shrub	PSSS
114	Tidal Fresh Marsh	PEM/SSR
114	Tidal Fresh Marsh	PEM/SSS
114	Tidal Fresh Marsh	PEM/SSTx
114	Tidal Fresh Marsh	PEM/USR
114	Tidal Fresh Marsh	PEM1S
114	Tidal Fresh Marsh	PEM1T
114	Tidal Fresh Marsh	PEMR

GIS Num	SLAMM California	NWI
114	Tidal Fresh Marsh	PEMRh
114	Tidal Fresh Marsh	PEMRx
114	Tidal Fresh Marsh	PEMS
114	Tidal Fresh Marsh	PEMSh
114	Tidal Fresh Marsh	PEMT
114	Tidal Fresh Marsh	PEMTx
114	Tidal Fresh Marsh	PUS/EMS
115	Irreg.-Flooded Marsh	E2EM/SSP
115	Irreg.-Flooded Marsh	E2EM/USP
115	Irreg.-Flooded Marsh	E2EM1P
115	Irreg.-Flooded Marsh	E2EM1Ph
115	Irreg.-Flooded Marsh	E2EMP
115	Irreg.-Flooded Marsh	E2EMPd
115	Irreg.-Flooded Marsh	E2EMPh
115	Irreg.-Flooded Marsh	E2EMPx
115	Irreg.-Flooded Marsh	E2US/EMP
116	Estuarine forested/shrub wetland	E2FO1P
116	Estuarine forested/shrub wetland	E2FOPx
116	Estuarine forested/shrub wetland	E2SS/EMP
116	Estuarine forested/shrub wetland	E2SS1P
116	Estuarine forested/shrub wetland	E2SS3P
116	Estuarine forested/shrub wetland	E2SSKh
116	Estuarine forested/shrub wetland	E2SSN
116	Estuarine forested/shrub wetland	E2SSP
116	Estuarine forested/shrub wetland	E2SSPh
117	Artificial reef	E2RSNr
117	Artificial reef	E2RSPr
118	Invertebrate reef	E2RF2M
119	Ocean Beach	M2AB/USN
119	Ocean Beach	M2AB1N
119	Ocean Beach	M2ABM
119	Ocean Beach	M2ABN
119	Ocean Beach	M2US/ABN
119	Ocean Beach	M2US2N
119	Ocean Beach	M2US2P
119	Ocean Beach	M2USN

GIS Num	SLAMM California	NWI
119	Ocean Beach	M2USP
120	Regularly-flooded Marsh	E2EM/USN
120	Regularly-flooded Marsh	E2EM1N
120	Regularly-flooded Marsh	E2EM1Nh
120	Regularly-flooded Marsh	E2EM1Ns
120	Regularly-flooded Marsh	E2EM1Nx
120	Regularly-flooded Marsh	E2EMKh
120	Regularly-flooded Marsh	E2EMM
120	Regularly-flooded Marsh	E2EMN
120	Regularly-flooded Marsh	E2EMNh
120	Regularly-flooded Marsh	E2EMNx
120	Regularly-flooded Marsh	E2US/EMN
120	Regularly-flooded Marsh	E2US/EMNh
121	Rocky Intertidal	E2RSN
121	Rocky Intertidal	M2RS/ABN
121	Rocky Intertidal	M2RS/ABNr
121	Rocky Intertidal	M2RS1N
121	Rocky Intertidal	M2RSM
121	Rocky Intertidal	M2RSN
121	Rocky Intertidal	M2RSNr
121	Rocky Intertidal	M2RSP
121	Rocky Intertidal	M2RSPr
122	Tidal Flat and Salt Panne	E2AB/USN
122	Tidal Flat and Salt Panne	E2AB3M
122	Tidal Flat and Salt Panne	E2ABM
122	Tidal Flat and Salt Panne	E2ABN
122	Tidal Flat and Salt Panne	E2US/ABM
122	Tidal Flat and Salt Panne	E2US/ABMh
122	Tidal Flat and Salt Panne	E2US/ABN
122	Tidal Flat and Salt Panne	E2US/ABP
122	Tidal Flat and Salt Panne	E2US1P
122	Tidal Flat and Salt Panne	E2US2N
122	Tidal Flat and Salt Panne	E2US2P
122	Tidal Flat and Salt Panne	E2US3N
122	Tidal Flat and Salt Panne	E2US3P
122	Tidal Flat and Salt Panne	E2USKh
122	Tidal Flat and Salt Panne	E2USN
122	Tidal Flat and Salt Panne	E2USNh
122	Tidal Flat and Salt Panne	E2USNx
122	Tidal Flat and Salt Panne	E2USP

GIS Num	SLAMM California	NWI
122	Tidal Flat and Salt Panne	E2USPh
122	Tidal Flat and Salt Panne	E2USPx
123	Riverine (open water)	R2AB3F
123	Riverine (open water)	R2ABF
123	Riverine (open water)	R2ABFr
123	Riverine (open water)	R2ABFx
123	Riverine (open water)	R2ABHr
123	Riverine (open water)	R2ABHx
123	Riverine (open water)	R2RBHx
123	Riverine (open water)	R2RSCr
123	Riverine (open water)	R2RSCx
123	Riverine (open water)	R2UBF
123	Riverine (open water)	R2UBFr
123	Riverine (open water)	R2UBFx
123	Riverine (open water)	R2UBH
123	Riverine (open water)	R2UBHr
123	Riverine (open water)	R2UBHx
123	Riverine (open water)	R2USA
123	Riverine (open water)	R2USAx
123	Riverine (open water)	R2USC
123	Riverine (open water)	R2USCr
123	Riverine (open water)	R2USCrx
123	Riverine (open water)	R2USCx
123	Riverine (open water)	R2USFr
123	Riverine (open water)	R2USJ
123	Riverine (open water)	R3RBF
123	Riverine (open water)	R3RBH
123	Riverine (open water)	R3RSC
123	Riverine (open water)	R3UBF
123	Riverine (open water)	R3UBFr
123	Riverine (open water)	R3UBFx
123	Riverine (open water)	R3UBH
123	Riverine (open water)	R3UBHx
123	Riverine (open water)	R3US1C
123	Riverine (open water)	R3US5A
123	Riverine (open water)	R3US5C
123	Riverine (open water)	R3USA
123	Riverine (open water)	R3USC
123	Riverine (open water)	R3USCx
123	Riverine (open water)	R3USJ

GIS Num	SLAMM California	NWI
123	Riverine (open water)	R4SBA
123	Riverine (open water)	R4SBAh
123	Riverine (open water)	R4SBAr
123	Riverine (open water)	R4SBAx
123	Riverine (open water)	R4SBC
123	Riverine (open water)	R4SBCr
123	Riverine (open water)	R4SBCx
123	Riverine (open water)	R4SBJ
123	Riverine (open water)	R4SBJr
123	Riverine (open water)	R4SBJx
123	Riverine (open water)	R4USA
123	Riverine (open water)	R4USAr
123	Riverine (open water)	R4USArx
123	Riverine (open water)	R4USAx
123	Riverine (open water)	R4USC
123	Riverine (open water)	R4USCx
123	Riverine (open water)	R4USJ
124	Riverine Tidal	R1ABVx
124	Riverine Tidal	R1UBT
124	Riverine Tidal	R1UBV
124	Riverine Tidal	R1UBVr
124	Riverine Tidal	R1UBVx
124	Riverine Tidal	R1USR
124	Riverine Tidal	R1USRr
124	Riverine Tidal	R1USRx
124	Riverine Tidal	R1USS
124	Riverine Tidal	R1USSx

GIS Num	SLAMM California	NWI
125	Tidal Channel	E2SB3N
125	Tidal Channel	E2SBM
125	Tidal Channel	E2SBMh
125	Tidal Channel	E2SBMx
125	Tidal Channel	E2SBN
125	Tidal Channel	E2SBNh
125	Tidal Channel	E2SBNx
125	Tidal Channel	E2SBP
126	Estuarine Open Water	E1AB3L
126	Estuarine Open Water	E1ABL
126	Estuarine Open Water	E1ABLh
126	Estuarine Open Water	E1ABM
126	Estuarine Open Water	E1UB2L
126	Estuarine Open Water	E1UB3L
126	Estuarine Open Water	E1UBL
126	Estuarine Open Water	E1UBLh
126	Estuarine Open Water	E1UBLx
126	Estuarine Open Water	E1UBN
126	Estuarine Open Water	E2AB3L
126	Estuarine Open Water	E2US2M
126	Estuarine Open Water	E2USM
126	Estuarine Open Water	E2USMh
126	Estuarine Open Water	E2USMs
126	Estuarine Open Water	E2USMx
127	Open Ocean	M1ABL
127	Open Ocean	M1UBL
127	Open Ocean	M1UBLx