SLAMM 6 beta Technical Documentation

Release 6.0.1 beta

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SLAMM 6 Technical Documentation

Sea Level Affecting Marshes Model, Version 6 beta

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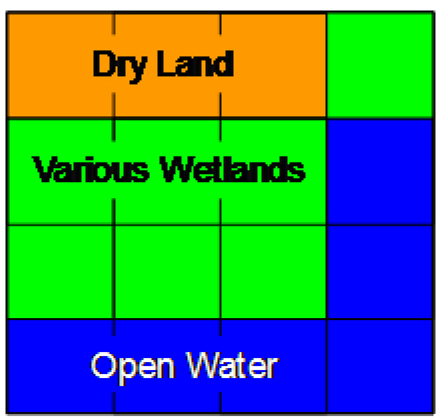
The SLAMM model would not exist were it not for the efforts of Dr. Richard A. Park who was instrumental in the creation of versions one through five and has provided many hours of uncompensated feedback in recent years.

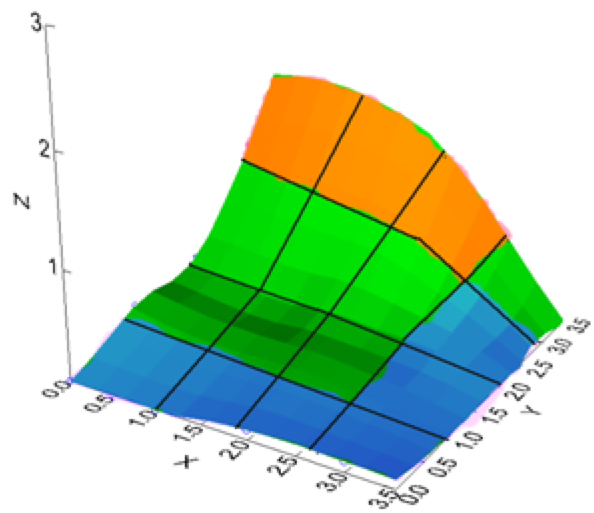
Introduction and Summary

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 1991, 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. 1991), 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 Upgrades

The SLAMM 6 model includes multiple upgrades from previous versions both as a result of feedbacks from other scientists working in the field (Kirwan and Guntenspergen, 2009) 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.
- **Salinity Model:** Multiple time-variable freshwater flows may be specified. Salinity is estimated and mapped at MLLW, MHHW, and MTL. Habitat switching may be specified as a function of salinity.
- **Integrated Elevation Analysis:** SLAMM will summarize site-specific categorized elevation ranges for wetlands as derived from LiDAR data or other high-resolution data sets.
- **Flexible Elevation Ranges** for land categories: If site-specific data indicate that wetlands 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 improves memory management considerably. Up to 4GB can now be utilized in 64-bit environments. (Hopefully a native 64-bit version will be available soon)
- **OpenGL 3D rendering** of SLAMM landscapes including rendering of tide ranges. This feature is important for understanding spatial relationships and for QA 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 / Users Manual.** Available in acrobat reader (pdf) format and also context-sensitive help in HTML help format.
- **Backwards Compatibility** to SLAMM5 – you may import SLAMM5 file structures into the new interface quickly and seamlessly.
- **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 for some reason.
- **New Maps**: Screen maps of elevations, salinity, and variable accretion rates are available in "Set File Attributes" and "debug-mode" execution as well as automatic pasting of maps to Microsoft Word. SLAMM land-cover colors are editable and choices are saved along with parameters in the SLAMM6 file.
- **Open Source –**
  - Non-distributable third party components (that interfaced with Excel and rendered maps in 3D) have been replaced.
  - Old portions of the code that haven't been used in years have been stripped away.
  - Object Pascal code has new object-oriented design.

- **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.

Model Execution

Within the SLAMM model, relative sea level change is computed for each site for each time step; it is the sum of the historic eustatic trend, the site-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). Alternatively, local SLR can be estimated as a function of eustatic trends and a spatial map of land uplift or subsidence.

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 not) if site-specific data are available. When high-vertical-resolution elevation data are available, the model will provide detailed statistics about the current elevation ranges of wetlands as a function of tidal range.

If a cell is 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 2m, although that assumption can be changed. (In one study, alternate management scenarios involving maintenance of dikes were simulated, Park et al. 1993.)

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; if the fetch (the distance across which wind-driven waves can be formed) is greater than 9 km, the model assumes moderate erosion. If a cell is exposed to open ocean, severe erosion of wetlands is assumed. Ocean beach erosion is modeled using a relationship reported by Bruun whereby recession is 100 times the change in sea level.

Wetlands on the lee side of coastal barriers are subject to conversion due to overwash as erosion of backshore and dune areas occurs and as other lowlands are drowned. 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; 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.

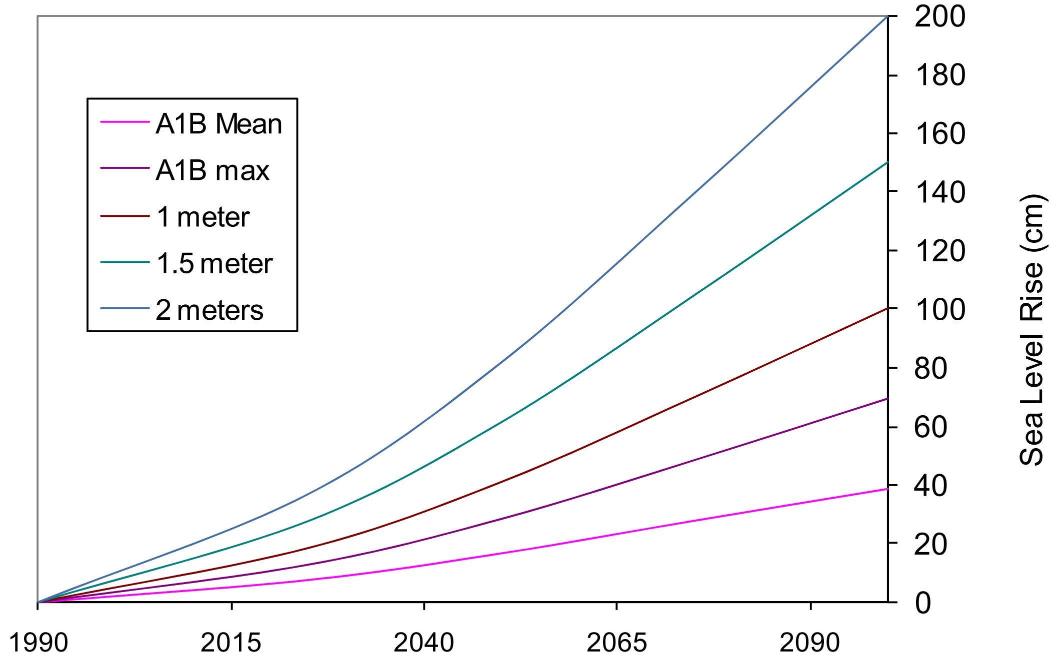
Sea Level Rise Scenarios

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 (2007) suggests that, taking into account possible model error, a feasible range by 2100 might be 50 to 140 cm. This work was recently updated and ranges were increased to 75 to 190 cm (Vermeer and Rahmstorf, 2009). A recent US intergovernmental report states "Although no ice-sheet model is currently capable of capturing the glacier speedups in Antarctica or Greenland that have been observed over the last decade, including these processes in models will very likely show that IPCC AR4 projected sea level rises for the end of the 21st century are too low." (US Climate Change Science Program, 2008) A recent paper by Grinsted et. al. (2009) states that "sea level 2090-2099 is projected to be 0.9 to 1.3 m for the A1B scenario, with low probability of the rise being within Intergovernmental Panel on Climate Change (IPCC) confidence limits." 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 2000. 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 <u>any</u> 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.

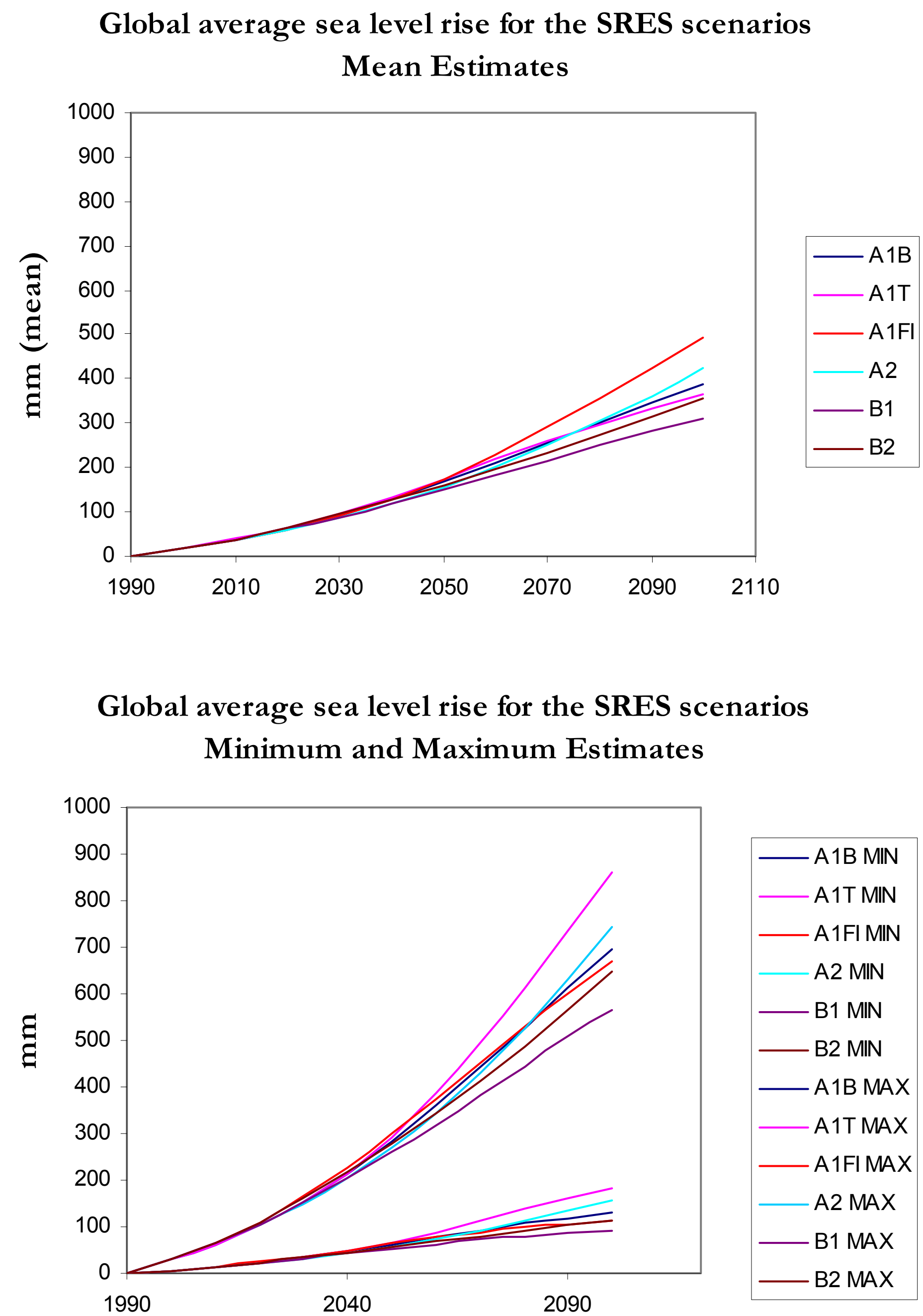
Figure 1: Scaling from IPCC scenario A1B to the 1, 1½ and 2 Meter Scenarios



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 is probably the most important SLAMM data requirement. Elevation data demarcates where salt water is predicted to penetrate and, when combined with tidal data, the frequency of inundation for wetlands and marshes. Elevation data also helps 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). USGS Digital Coast 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:

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

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 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.

There is a temporal aspect to the conversion of the Digital Elevation Map (DEM) datum as well. The basic steps taken in SLAMM to process elevation data prior to imposing SLR scenarios 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). We can then project local sea level rise onto this map to predict future conditions.

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. The model does this by estimating 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 Tide Level	Salt Boundary
Ocean Beach	Mean Lower Low Water	Salt Boundary
Scrub-Shrub	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 further discuss the methods of the 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 wetland's 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.

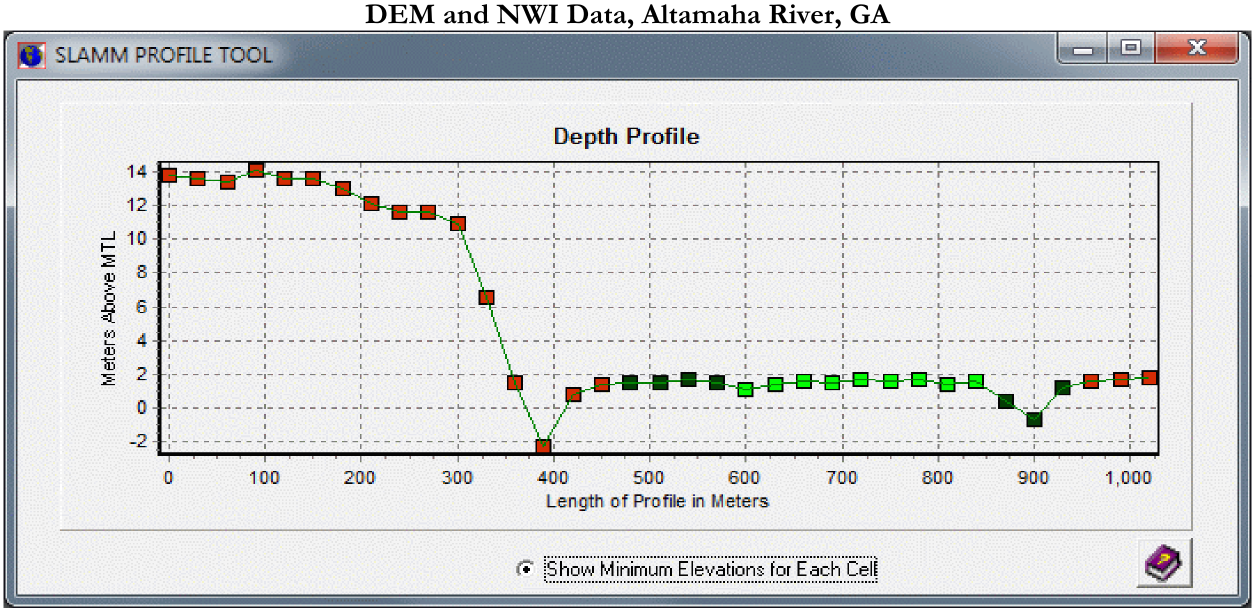
Elevation Data Quality Assurance

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)**;
- errors due to the accuracy of the DEM or DEM interpolation procedures.

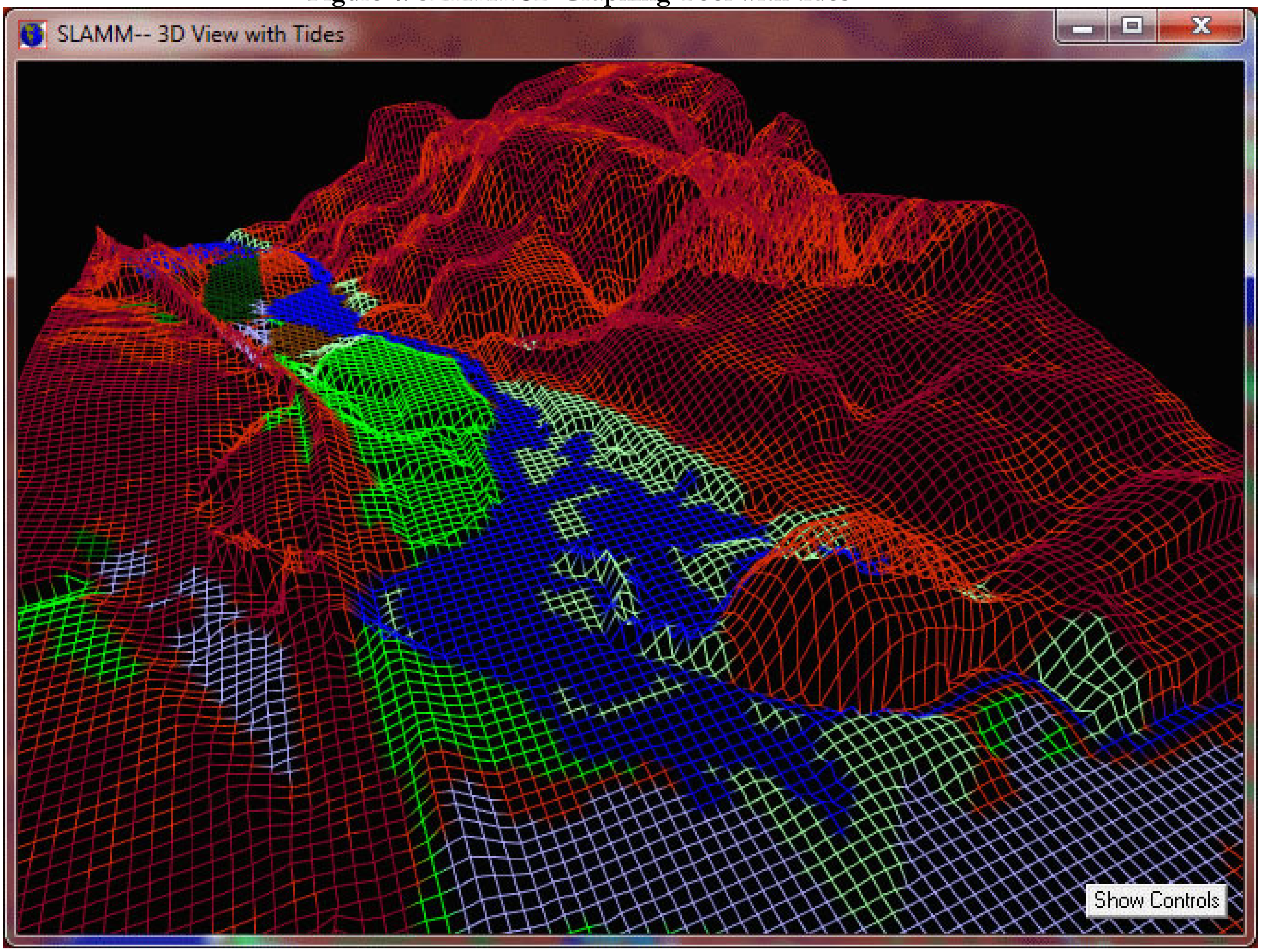
A number of quality assurance tools have been integrated into the SLAMM 6 interface to help assess these potential glitches. For example, an elevation profile tool may be used to graphically represent the Elevation profile of any line drawn on the site map.

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



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. SLAMM will then run using the selected time-step to 2100.

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 2007a)

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
1000	=	(mm/m).

When projecting sea level rise, a question arises as to which portion of the site-specific historic sea level rise trend occurred due to global effects. To address this, when SLAMM is run with IPCC and "Fixed" Scenarios, the global historic trend is subtracted from the local historic trend so that "truly local" effects can be isolated. These "truly 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 2007a §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 sea level rise estimates within the SLAMM model project forward from 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:

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

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:

$$SLR_{TModel} = SLR_{TModel} - GlobalSLR_{T0} \quad \textbf{(6)}$$

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

$$SLRise = SLR_{TCurrent} - SLR_{TPrevious} \quad \textbf{(7)}$$

where:

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

$$MinElev_{Category,t} = MinElev_{Category,t-1} + DeltaT \cdot Accrete_{Category} - SLRise \quad \textbf{(8)}$$

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

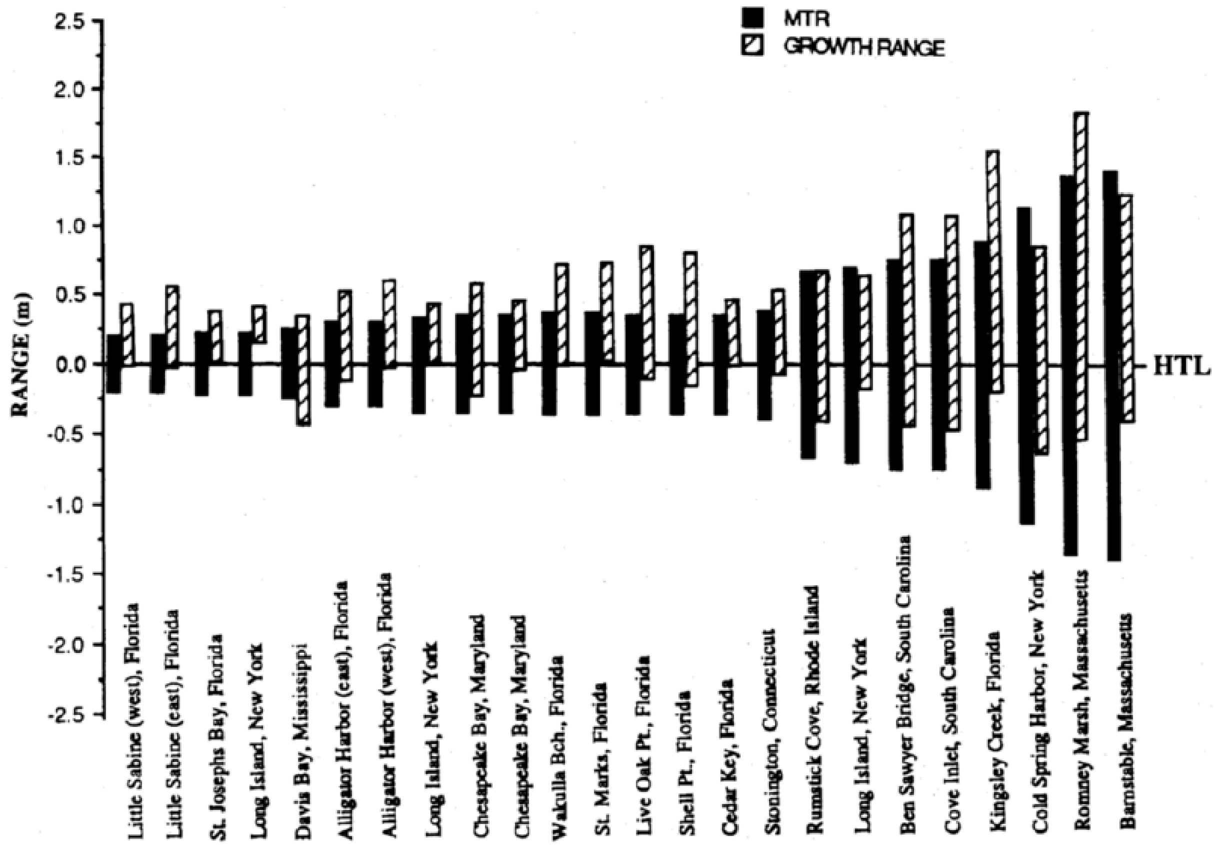
$$MinElev_{Category,t} = MinElev_{Category,t-1} - SLRise \quad \textbf{(9)}$$

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).



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 thrown off by any changes in land cover classes 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 now be modified to allow a new elevation-range to wetlands-class relationship (new SLAMM 6 capability). 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.

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 or they will potentially convert to another category at "time zero." Due to the importance of fresh water flows for these wetlands, whenever possible a salinity model should be utilized rather than an elevation range model to determine the conversions for these two model categories.

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 **(19)**.
- **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.

- **Overwash:** Barrier islands of under 500 meter width are assumed to undergo overwash during each 25 year time-step due to storms encountered. Beach migration and transport of sediments are calculated.

- **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.

Each of SLAMM's cells may be composed of multiple 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.

Erosion

Under equilibrium conditions, erosion and deposition balance and wetlands are not lost. However, even historic sea level rise coupled with local subsidence has upset coastal equilibrium in many parts of the world (Bird, 1986; Bruun, 1986). Although the processes of erosion can be expressed by detailed quantitative relationships, this level of detail is often unnecessary. Rather, qualitative relationships are defined and used as thresholds for including constant rates of wave erosion in simulating the localized loss of wetlands. The effects of severe storms are included in these average values. In the present implementation of SLAMM 6.0, constant erosion is triggered only when the average fetch exceeds 9 km (cf. Knutson et al., 1981).

A qualitative relationship between maximum fetch and erosion has been developed that affects other portions of the spatial model:

Max. Fetch less than 9km	Erosion = None
Max. Fetch >9km to 20km	Erosion = Heavy
Max. Fetch greater than 20km	Erosion = Severe *(affects dry-land)*

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.

Coastal Engineering Structures

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 check the NWI dike coverage such as USGS topographical maps and local sources of information.

The two protection scenarios available within SLAMM 6 represent further construction of dikes around all developed areas, or all dry land, respectively. Areas so protected are not allowed to convert to other habitat types in the simulations. Enclosed wetlands are assumed to be maintained in their initial condition until there is greater than 2 meter inundation, at which time small dikes are assumed to fail.

Accretion

Previous SLAMM versions treated sediment accretion as a site or sub-site characteristic, based on measured accretion rates for each habitat type within a defined region. Accretion rates could vary spatially and by habitat type, but did not vary temporally.

However, accretion can be highly variable within a site and even within a habitat type; it is spatially differentiated, depending on a number of key factors, including habitat, vegetation (biomass), elevation, distance to river (or tidal channel), tidal range and salinity. It can then vary temporally as a function of sediment concentrations or changes in cell elevations.

One possible modification to the SLAMM model could be to utilize the Morris (2002) model of accretion. Within this model, accretion is a function of the elevation of the marsh platform, vegetative biomass, vegetative trapping efficiencies, and the concentration of sediments in the water. The Morris model can become complex given multi-species marsh platforms and a more flexible approach may be warranted. An alternative approach is proposed here that modifies a maximum theoretical accretion rate considering cell elevation, distance to channel, and salinity (if relevant). However, as shown below, the model is flexible enough so that results from the Morris model can be used to directly drive the SLAMM elevation to accretion rate relationship.

It is also worth noting that the SLAMM accretion relationships are not mechanistic, (taking into account vegetation sediment trapping efficiency, inundation frequency, and sediment concentrations, for example) but rather are empirical relationships defined between accretion rates and cell elevations (among other factors).

The calculation of cell-specific accretion rates is calculated as:

$$A_{cell} = A_{Elev}(D \cdot S) \qquad \textbf{(10)}$$

where:

A_{cell} = predicted accretion rate for a cell, (mm/year)

A_{Elev} = accretion rate for a cell as a function of elevation alone (See **(12)**)

D = factor representing distance to river or tidal channel (unitless) (See **(13)**)

S = salinity factor representing salinity effects (unitless) (See **(14)**)

Elevation can affect the spatial distribution of accretion rates within a habitat type in various ways. Inundation time for any cell within the model grid depends on its elevation with respect to tides. Mean High Tide is often the tidal datum used to calculate inundation times for any particular elevation point within tidal range. As cell elevation decreases, inundation time and depth increases, allowing more time for sediment settling and providing a greater source volume of suspended sediment. Furthermore, productivity of vegetation may vary across the elevation range of a particular habitat type, which will affect accretion rates. For example, within a habitat, some species may produce the most above-ground biomass at lower elevations within its typical elevation range. Above-ground biomass in a cell will affect mineral accretion via sediment trapping efficiency. There is always a trade-off between above and below-ground biomass, with one affecting mineral accretion and the other affecting organic accretion. Elevation-productivity rules will vary depending on the biophysical conditions in each particular coastal wetland.

Elevation range within a habitat as a driver of accretion rates may be particularly important in broad, shallow coastal wetlands where a habitat's horizontal spread may be large and accretion variability also spatially high. In addition, elevation may be relatively more important than other factors in wetlands with lower levels of variability in salinity, or wetlands that lack a strong point source of sediment (e.g. where seasonal ocean currents dominate sediment distribution rather than a river source).

The SLAMM modeling approach was designed to maximize flexibility in calculating accretion relationships. A cubic equation is used to define the shape of the curve, relating the inverse of elevation to the curve's shape:

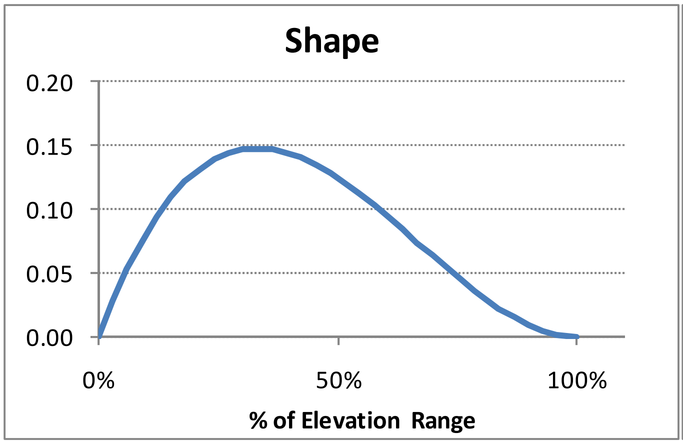
$$ElevPctile = (Elev - ElevMin)/(ElevMax - ElevMin)$$

$$Shape = a\,(1 - ElevPctile)^3 + b\,(1 - ElevPctile)^2 + c\,(1 - ElevPctile) \qquad \textbf{(11)}$$

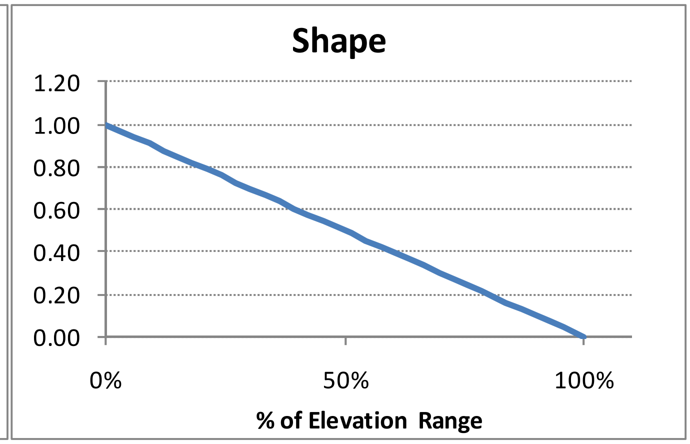
where:

Elev	=	cell's elevation relative to MTL (meters);
ElevMax	=	maximum elevation range for wetland (meters above MTL);
ElevMin	=	minimum elevation range for wetland (meters above MTL); and
a, b, c	=	cubic coefficients that determine shape of curve (unitless).

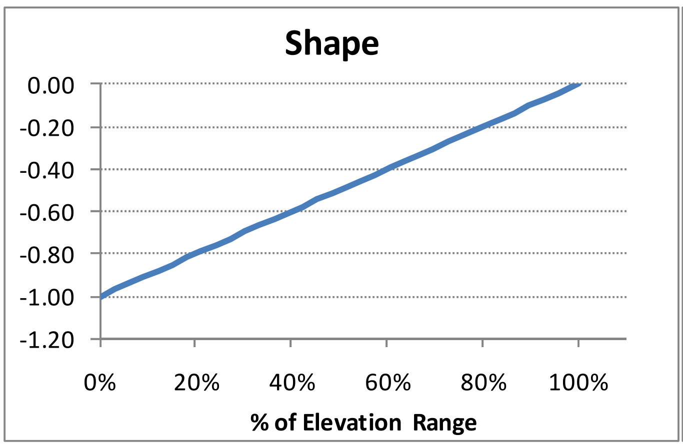
This equation is then applied to a range between then defines the "shape" curve which is extremely flexible as shown here:



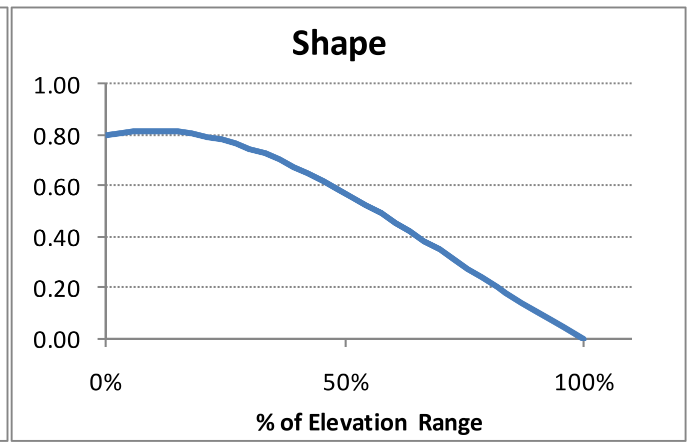
a= -1; b= 1; c= 0.



a= 0; b= 0; c= 1.



a= 0; b= 0; c= -1.



a= -1; b= 0.8; c= 1.

Finally, cell-specific accretion is derived as a function of the shape curve and the minimum and maximum accretion rates.

$$ShapePctile = \frac{(Shape(Elev) - MinShape)}{(MaxShape - MinShape)}$$

(12)

$$AElev = MinAccr + ShapePctile\left(MaxAccr - MinAccr\right)$$

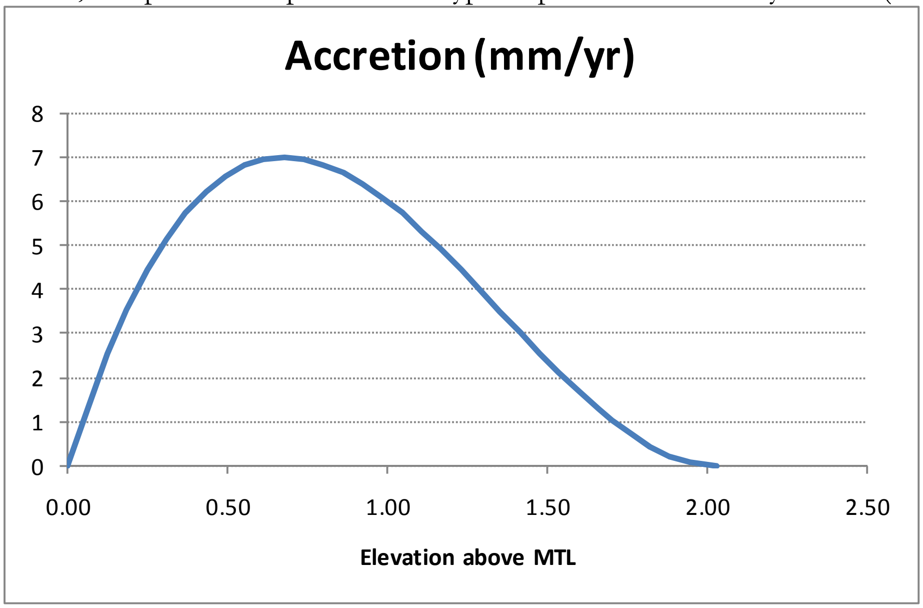
where

A_{Elev} = accretion rate for a cell as a function of elevation alone

MaxAccr = theoretical maximum accretion rate for this site given optimal elevation, distance to tidal channel, and salinity. This factor may be calibrated so that modeled initial conditions match data for the habitat type (from literature, regional data or site-specific data). If alternate calibrations are possible, this factor can also be tested for sensitivity. (mm/year)

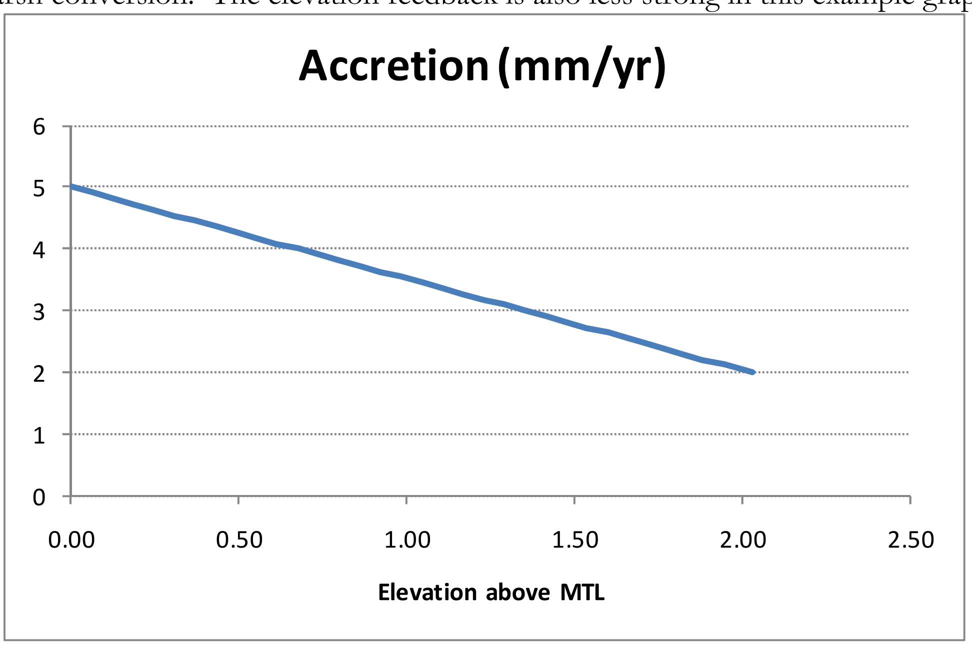
MinAccr = Minimum accretion for wetland type based on elevation (mm/year)

Using this equation, it is possible to produce the type of parabola defined by Morris (2002):



Graph showing predicted accretion rates as a function of elevation with the following parameters:
Min. Accretion = 0 mm/year; Max Accretion = 7 mm/year; Min Elev = 0 m; Max Elev = 2.02 m; a=-1; b=1. c=0.

Alternatively it may be more appropriate to assume that accretion rates do not drop to zero until the marsh has reached the "unstable zone" below the minimum elevation at which case SLAMM predicts marsh conversion. The elevation feedback is also less strong in this example graph:



Graph showing predicted accretion rates as a function of elevation with the following parameters:
Min. Accretion = 2 mm/year; Max Accretion = 5 mm/year; Min Elev. = 0 m; Max Elev. = 2.02 m; a=-0; b=0. c=1.

As shown above, the "shape" formulation provides maximum flexibility in defining any type of positive or negative relationship between elevations and accretion rates. An Excel spreadsheet is automatically installed along with SLAMM 6.0 that can derive accretion to elevation curves based on any parameter choices so they can be fit to site-specific data. This file is located in the same directory as the SLAMM6 executable.

In many cases, defining a negative relationship between accretion and cell-elevations may be warranted (such that accretion rates increase when elevations are reduced as a function of increased inundation). In this case, the elevation of the entire marsh surface will tend to equilibrate over time as lower marsh surfaces move up vertically at a faster rate while higher marsh surfaces move more slowly. If SLR is sufficient the marsh platform will move down towards the minimum elevation until it is all lost simultaneously. Predicting the timing of such an all-or-nothing, threshold- type response is difficult as it requires a precise accounting of the feedback between surface elevation and vertical accretion. Model predictions also do not take into account potential exacerbating factors that could push the platform beyond the critical threshold (such as yearly variation in weather patterns or marsh predation).

The **distance** from a cell to a river or tidal channel will also affect the spatial distribution of accretion rates. This factor is likely most important in coastal wetlands where there is a strong point source of sediment, such as a river. The availability and quality (particle size) of mineral sediment as a driver for accretion can be expected to vary along a continuum from its source. Typically, deposition rates are higher the closer a cell is to a river or tidal channel. For any particular cell, the relative volume of mineral sediment available will also depend on characteristics of the nearest channel: channel type (e.g. distributary vs. blind tidal) and channel order (~ channel size relative to tidal prism). Rules for this piece of the algorithm could be based on channel size and type. One approach could be a simple rank ordering of channels based on observed or expected relative proportion of total sediment volume. In a river estuary, distance to a channel is also related to salinity distribution and the distribution of vegetation species and productivity. The distance factor may be one way to indirectly account for some of that variability.

Note that the site-specific data that we intended to develop this model with were not sufficient to define such a relationship. Therefore the distance to channel relationship, the shape of the curve, and even the existence of such a relationship at a given site should be treated as theoretical.

The distance to channel factor "D" is characterized as a unitless factor to be multiplied by the maximum accretion rate as adjusted for elevation effects. Initially a linear relationship has been used to parameterize the relationship between distance to channel and accretion factor "D" but a minimum value for D will exist such that baseline or non-channel influenced accretion may also be modeled.

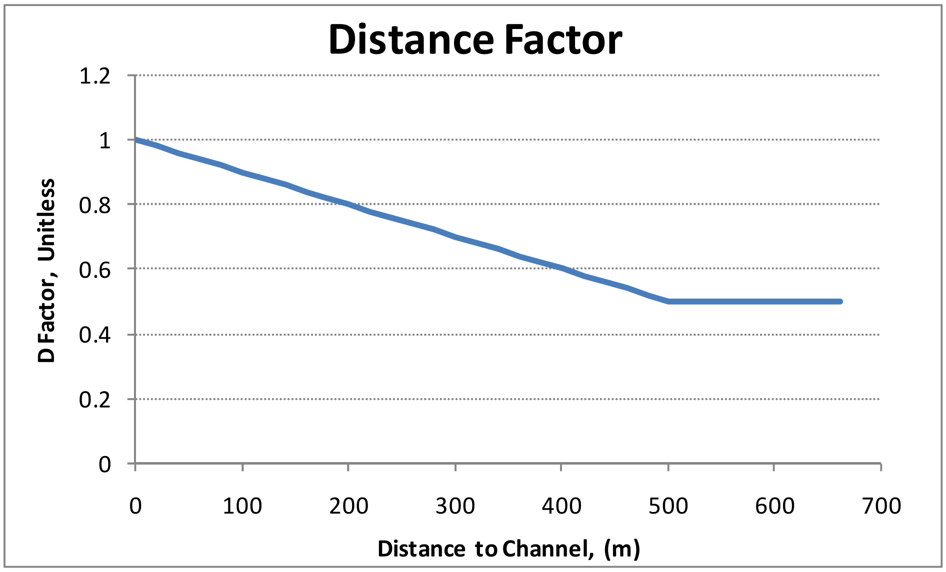
$$D = 1 - D2Channel \; / \; DistEffectMax \;\; (1-D_{min}) \qquad \textbf{(13)}$$

$$\text{If } D2Channel > DistEffectMax \text{ then } D = D_{min}$$

where:

D2Channel	=	distance to channel in meters;
DistEffectMax	=	beyond this distance proximity to channel has no additional effect (m);
D_{min}	=	minimum value for distance effect scaling (unitless).

If data do not exist to parameterize this relationship then DistEffect may be set to zero and D_{min} can be set to 1.0.



Graph showing predicted distance correction factors with the following parameters:
Dmin = 0.5; DistEffect = 500 meters.

The **biomass** of vegetation in a cell will affect the accretion rate of that cell. Within a habitat type, the species composition and biomass can vary significantly across space within a site. Above-ground biomass will affect the efficiency of mineral sediment capture, with greater biomass tending to capture more sediment. Below-ground biomass will affect organic accretion rates. Total biomass can vary within a habitat, but root:shoot ratios may also vary. A shifting root:shoot ratio may determine whether mineral or organic accretion is more important in a cell. The importance of this trade-off to overall accretion is difficult to determine and is likely site-specific. Some species can be very productive (e.g. Schoenoplectus maritimus on the west coast or Spartina alterniflora on the east/Gulf coasts), while others may be less productive (e.g. Schoenoplectus americanus) and may therefore be less efficient at capturing sediment. Vegetation productivity in a cell will vary depending on factors such as elevation, sediment quality, and the salinity of both water column and soil. Some of these drivers may be partially captured in the elevation and distance-to-channel factors. Other factors that may affect productivity include temperature, light (as affected by turbidity), nutrient regime, and CO_2 concentration. A biological process that will affect biomass productivity is herbivory.

At some sites, such as Port Susan Bay, populations of snow geese and swans have been expanding greatly over the past 15 years, and over-wintering time has lengthened. There is some anecdotal evidence that present populations may be removing enough biomass from tidal marshes to significantly affect stem density and tidal marsh patchiness, which may be impacting accretion/erosion dynamics. The effect of herbivory is less likely to be related to the elevation and distance-to-channel factors, which is one reason the biomass factor may be an important tool for testing vulnerabilities.

The model of Morris (2002) estimates biomass as a function of inundation depth at high tide. These effects will presumably be incorporated in the elevation correction calculation **(12)**. At this time, it is suggested that changes in biomass that are not driven by elevation (e.g. herbivory) be accounted for using different sub-sites over which different accretion rates occur (and different parameters are used for equation **(12)**. If site-specific data indicate that it would be predictive to include biomass on a cell-by-cell basis, this could be included in the model at that time.

The **salinity** regime of a cell will affect its accretion rate. In some estuaries a "turbidity maximum" zone occurs where the interaction of fresh and salt water results in a relatively high concentration of suspended sediment. One aspect of this may be a zone where river-borne clay particles flocculate and settle, under the influence of changing salinity. There are likely a number of factors that influence the relative importance of the turbidity maximum zone for an estuary, including estuary size, tide scale (micro, meso, or macro), level of mixing vs. stratification, geometry in the mixing zone including lateral space and vertical depth at low and high tides, dike effects on hydrodynamics, and vegetation composition in the mixing zone. Salinity also affects vegetation species distribution and productivity throughout the estuary. Pore water salinity may be a more important driver of vegetation dynamics than the salinity of the water-column, especially in coastal wetlands with high variability in water column salinity. The seasonality of salinity may also influence sediment dynamics, particularly on the west coast where strong seasonal changes in freshwater flows (low flows during the summer growing season) may affect sediment supply, seasonal sediment quality, the importance and location of the turbidity maximum zone, and overall salinity distribution.

The SLAMM model does contain a simple salinity model that assumes a salt-wedge estuary. If site-specific data indicate that accretion rates cannot be described on the basis of elevation and distance to channel alone, a salinity component can be utilized.

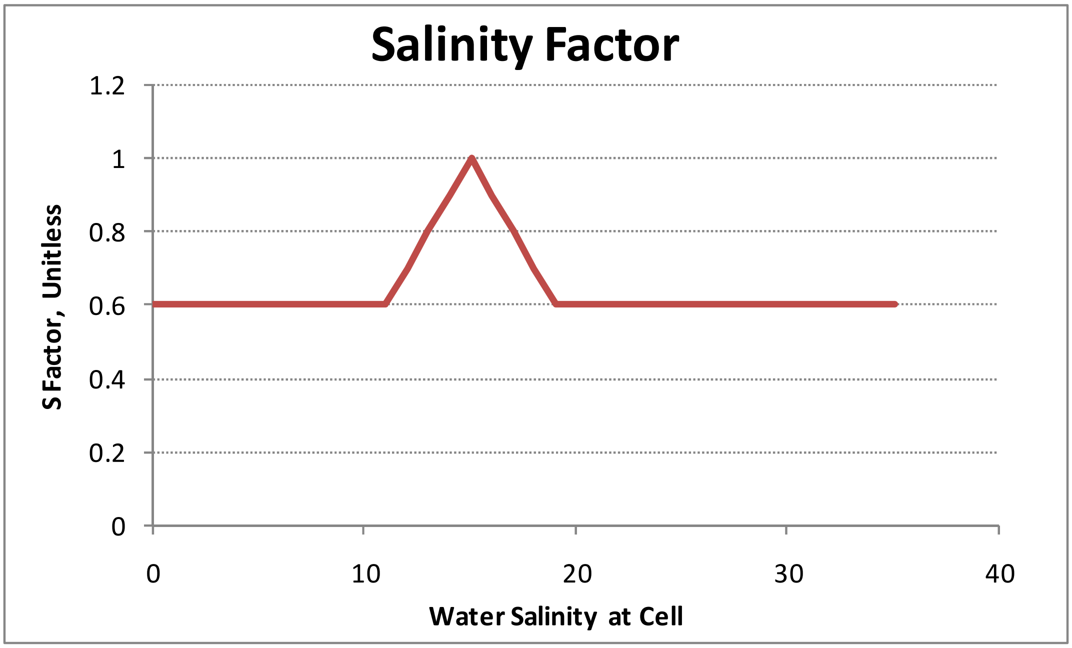
If $Salinity_{Cell}$ in $[Salinity_{TMax} - (TmaxZone/2), Salinity_{TMax} + (TmaxZone/2)]$ then:

$$S = S_{NonTMax} + (1 - S_{NonTMax})\ (1 - |Salinity_{TMax} - Salinity_{Cell}| \ / \ (TMaxZone/2) \qquad \textbf{(14)}$$

Otherwise: $S = S_{NonTMax}$

where:

$Salinity_{Cell}$	=	salinity at given cell (ppt)
$Salinity_{TMax}$	=	intermediate salinity level at which maximum accretion rate occurs (ppt)
$S_{NonTMax}$	=	accretion limitation factor with no salinity effect (unitless)
TMax Zone	=	range of salinity over which there is some salinity effect (ppt)



Graph showing predicted salinity correction factors (S) with the following parameters: Salinity_{TMax} = 15; TMaxZone = 10; $S_{NonTMax}$ = 0.6

The salinity-feedback portion of the SLAMM6 accretion model remains experimental and hypothetical as data required to develop such a relationship have not been available.

Salinity Module

The SLAMM salinity model estimates a spatial map of salinity under conditions of low tide, mean tide, and high tide. This may be required 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.

The SLAMM 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.

Boundary Conditions

- As in the previous model version, river and tributary pathways are defined by the user (center of the river channel).
- The user has the capability to enter a fresh water flow for each river and tributary. When tributaries join the main channel, their fresh water flows are considered to be additive.
- Fresh water flows may be entered in a time-series to evaluate different long-term scenarios of fresh water flow.
- Bathymetry is also a new 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 water is an additional model parameter.
- The slope of the salt wedge is assumed to be linear and serves as a calibration parameter for this model.

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.

$$Salinity_{cell} = Salinity_{SaltWater} * fraction_{SaltWater} + Salinity_{FreshWater} * fraction_{FreshWater} \quad \textbf{(15)}$$

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, assumed to be 30 ppt in the current model implementation.
$fraction_{FreshWater}$	=	$1- fraction_{SaltWater}$

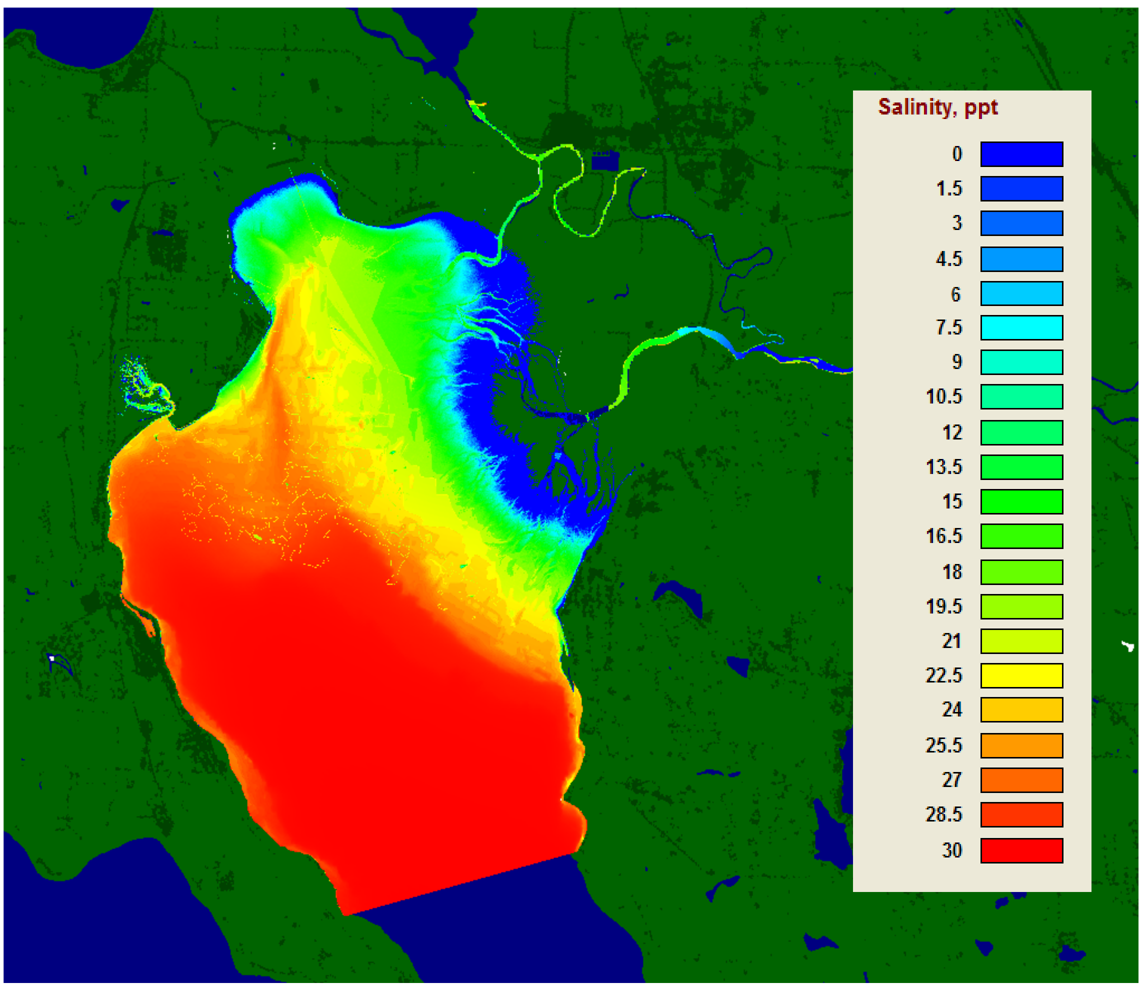
Within the river itself, the river's cross section perpendicular to each segment of the water is calculated as a function of the river's bathymetry. Fresh water flows are assumed distributed across this river basin. Salinity will intrude up the estuary when elevations and mean tide range permit and salinities then calculated.

Within the estuary where river flows are not 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.
- Fresh water is distributed based on vector of flow into the estuary and bathymetry of estuary.
- Complex hydrodynamic processes such as water density effects, conservation of momentum, advection and diffusion are not explicitly included in this model. (It would be a fairly

straightforward procedure to link raster output created by a hydrodynamic model into the SLAMM model. Minor modifications to the code would be required to support such linkage, however.)

- 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 (which is a constant model parameter) and the distance to the end of the salt wedge which is assumed to be the limit of freshwater flow influence as defined by the user. (Salt elevations may be examined in "debug mode" along with predicted salinity maps.)
- 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.



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

At Time N

1. *salt height*$_{Tide}$ of the estuary segment N is calculated based on change in MTL (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*$_{TN}$ * *retention time*
   c. Water height = FTable height (Salt Volume + Fresh Volume)
4. Calculate Cell Salinities$_{Tide}$ as a function of salt water and fresh water volumes.

$$saltheight_{Tide}=TideHeight\text{-}(MaxRn\text{-}RSeg)\cdot SliceIncrement\cdot 1000\cdot SaltWedgeSlope \qquad \textbf{(16)}$$

$$retentiontime_{Time-zero}=\frac{Volume_{FreshWater}}{Flow_{FreshWater}} \qquad \textbf{(17)}$$

$$Volume_{FreshWaterTN}=\frac{Flow_{FreshWaterTN}}{RetentionTime} \qquad \textbf{(18)}$$

where

$saltheight_{Tide}$	=	the estimated elevation of the salt wedge in meters;
TideHeight	=	MLLW, MTL, or MHHW in meters;
MaxRn	=	the maximum river segment number with freshwater 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 (m/m);
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).

Habitat Switching Functions

Habitat switching functions (as a function of elevation) have been made more 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.

Estuarine beaches no longer convert to tidal flats. Based on the NWI definition and also several LiDAR analyses, the default elevation range for this land-cover class is assumed to extend down to MLLW (though the exact range is now variable as discussed above).

Overwash

As erosion of backshore and dune areas occurs and as other lowlands are submerged, wetlands on the lee side of coastal barriers are subject to conversion due to overwash, the process by which sediments are carried over the crest of the barrier and deposited onto adjacent wetlands. This process is simulated only for areas having a beach and only during the time step in which the lowland is breached.

SLAMM default assumptions are that 50% of the adjacent transition marsh and salt marsh, and 25% of mangrove (if present) in the adjacent 500m to lee is converted to beach and tidal flat; the percentages are professional judgment based on observations of existing overwash areas (Leatherman and Zaremba, 1986). Beach migration occurs as well with estuarine beach within 500m of the ocean beach advancing by 60m. The front edge of the ocean beach will recede by 30m. Dry land adjacent to ocean beach will be converted to ocean beach. These professional judgments may now be edited as part of the sub-site input parameters.

SLAMM 6 assumes that a barrier island or narrow peninsula is present when there are estuarine waters, salt marsh, scrub-shrub, irregularly flooded marsh, or mangroves within 500m to lee of the front edge of an ocean beach. The user may specify the frequency of large-storms during which overwash is predicted to occur. All overwash effects are estimated to be localized to the 500 meters to the lee of the front edge of the ocean beach. The 500 meter cutoff may also be edited as a model parameter.

Conversion of Wetlands

If the lower boundary of the wetland class has exceeded the minimum elevation, the fraction lost is calculated using the slope **(19)**.

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:

$$FracLost_{Cat} = \frac{\left(\dfrac{LowBound - MinElev_{Cat,t}}{\tan Slope} \right)}{Width_{Cat}} \qquad \textbf{(19)}$$

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 wetland categories that are adjacent to water, erosion takes place if the maximum fetch for the given cell is greater than 9km. Tidal flats are assumed subject to erosion regardless of the extent of wave setup.

$$Additional\ FracLost_{Erosion} = \Delta T \left(\frac{Erosion_{Category}}{Width_{Category}} \right) \qquad \textbf{(20)}$$

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 **(19)**.

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 SLAMM 6.0.1 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 [grey-blue 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]
- Diked (lack of connectivity assumed) [yellow 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..

The SLAMM Decision Tree

This section details the decision tree that SLAMM uses when converting one land-cover class to another in the event of inundation or erosion. Table 3 summarizes the conversions of each land type due to inundation and erosion. A discussion of how each SLAMM land-cover category is processed then follows.

Table 3: Assumed Effects of Inundation and Erosion.

	Inundation: *Non-adjacent to open water or Fetch < 9km (non tropical systems)*	**Erosion:** *Adjacent to Open Water and Fetch > 9km (erosion)*
Converting From	**Converts To**	**Converts To**
Dry Land	Transitional salt marsh, ocean beach, or estuarine beach, depending on context (see below)	Erosion of dry land is ignored.
Swamp	Transitional salt marsh	Erosion to Tidal Flat
Cypress Swamp	Open Water	Erosion to Tidal Flat
Inland Fresh Marsh	Transitional salt marsh	Erosion to Tidal Flat
Tidal Swamp	Tidal Fresh Marsh	Erosion to Tidal Flat
Tidal Fresh Marsh	Irregularly Flooded Marsh	Erosion to Tidal Flat
Scrub-Shrub, Irregularly Flooded Marsh	to Regularly Flooded Marsh	Erosion to Tidal Flat
Regularly Flooded Marsh	to Tidal Flat	Erosion to Tidal Flat
Mangrove	to Estuarine Water	Erosion & Inundation to Estuarine Water
Ocean Flat	to Open Ocean	Erosion to Open Ocean
Tidal Flat	Erosion, Inundation to Estuarine Water	Erosion to Estuarine Water
Estuarine Beach, Ocean Beach	open water	Erosion to open water

Categories 1 and 2: Developed and Undeveloped Dry Land:

Elevations for these categories are adjusted for sea level rise. If the lower elevation of this category drops below the salt boundary then inundation takes place. (Developed dry land and undeveloped dry land are only differentiated if the "protect developed" option is chosen.) When protections are in place ("protect all," or "protect developed") then no inundation takes place. The inundation decision tree is as follows.

- If a cell is "adjacent to water" (within 500m of ocean water) then convert to Ocean Beach.
- Otherwise if a cell is "adjacent to water" and "erosion" is "severe" (maximum fetch > 20 km) then convert to "estuarine beach"
- Otherwise if a site is "tropical" and a cell is "near water" (within 6km of water) then convert to "mangrove"
- Otherwise convert the category to "transitional salt marsh / scrub-shrub"

For undeveloped dry land, soil saturation can occur. The maximum elevation of freshwater wetlands, below dry land, is taken to be the elevation of the water table. Similar to the salt boundary, this datum is maintained as sea-level rise occurs, thus accounting for the conversion of dry land to freshwater wetlands. **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.

If the 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:

$$WaterTable = MinElev_{NearWetland} + \left(SLRise / 0.91\right) \cdot e^{-0.776 - (0.0012\ Distance)} \qquad \textbf{(21)}$$

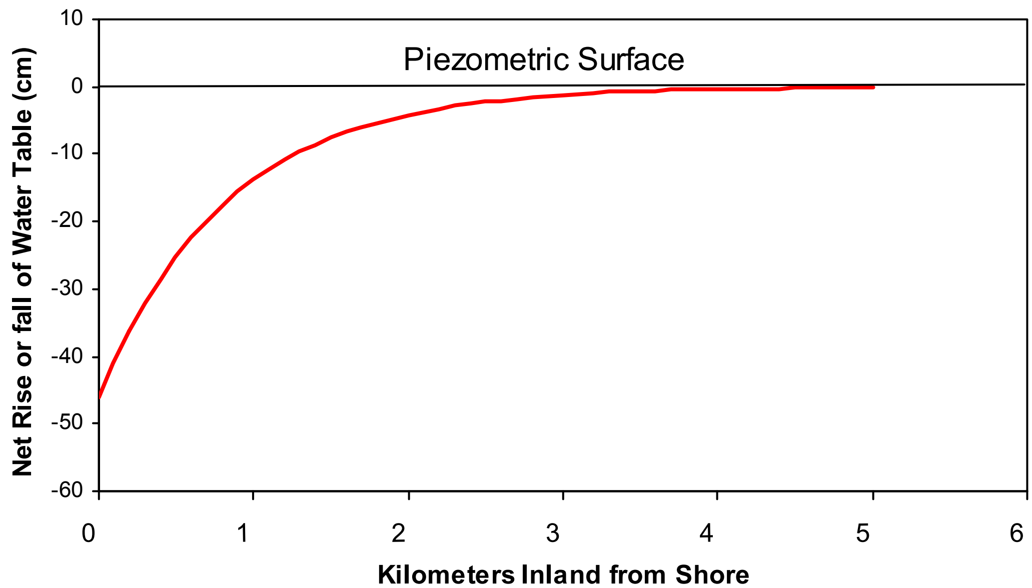
where:

WaterTable	=	Estimated water table at the current dry land cell (m);
$MinElev_{NearWetland}$	=	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 **(21)** is adapted from Carter et al. (1973, figure VII-16). Figure 5 below shows the predicted extent of water table migration due to each 0.91 meters of sea level rise.

If the estimated water table is greater than the elevation of the dry land, saturation takes 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.

Figure 5: Water Table Rise Near Shore, Based on Carter et al., 1973



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.

Category 3: Swamp (Palustrine forested broad-leaved deciduous)

The elevation of the swamp is adjusted for sea level rise **(8)**. As is the case for all swamp and marsh categories, accretion is added unless the swamp is protected by a dike in which case accretion is assumed to be zero **(9)**. In version 6: Accretion in the model is hard-wired to 0.3 mm/year based on data taken in GA swamps (Craft et. al, 2008).

If the site falls below its lower elevation boundary (default being the salt boundary) then the swamp is converted to transitional marsh scrub-shrub (non-tropical system) through inundation. Conversion is to mangrove in a tropical system.

If the swamp borders on open water and erosion is predicted to be heavy (maximum fetch 9 km or greater) then erosion of the swamp to tidal flats will occur **(20)**.

Category 4: Cypress Swamp (needle-leaved deciduous)

Cypress Swamp is processed almost identically to the "Swamp" category above. The one exception occurs during inundation. Cypress swamp is converted directly into estuarine water in a non-tropical system rather than scrub-shrub.

Version 6: Accretion in the model is hard-wired to 0.3 mm/year based on data taken in GA swamps (Craft et. al, 2008).

Category 5: Inland Fresh Marsh (Lacustrine, Palustrine, and Riverine emergent)

As in the case of the swamps, the elevation of the fresh marsh is adjusted for sea level rise depending on whether it is protected by a dike **(8)** and **(9)**.

If after the elevation adjustment, the lower edge of the marsh is below the lower elevation boundary (default is the salt boundary) then the marsh is converted to mangrove (tropical system and within 6km of water) or transitional salt marsh (non-tropical system or far from water) through inundation **(19)**.

Category 6: Tidal Fresh Marsh (Riverine tidal emergent)

Elevations are adjusted with equations **(8)** and **(9)**. If the elevation dips below the lower elevation boundary then the marsh is converted to mangrove (tropical system and within 6km of water) or irregularly flooded marsh (non-tropical system or far from water) through inundation **(19)**.

The SLAMM default lower elevation boundary for tidal fresh marsh is the salt boundary (for backward compatibility) but this elevation should probably be reduced by the user (see the discussion in *Conceptual Model Verification* above.)

Category 7: Transitional Salt Marsh (Estuarine intertidal scrub-shrub broad-leaved deciduous)

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and Erosion are calculated using the lower elevation boundary for this category (MHHW is the default lower elevation boundary). Inundated transitional salt marsh is assumed to convert to regularly flooded marsh. Also see the sections on "Conversion of Wetlands" and "Coastal Engineering Structures" above.

Category 8: Regularly Flooded Marsh (salt marsh, estuarine intertidal emergent)

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion are calculated using a default of Mean Tide Level as the lower elevation boundary for this category. Inundated regularly flooded marsh is predicted to convert to tidal flat.

Category 9: Mangrove (Estuarine intertidal forested and scrub-shrub broad-leaved evergreen)

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion are calculated using a default of Mean Lower Low Water as the lower elevation boundary for this category. Under conditions of inundation or erosion, mangroves convert to open water. (See "Conversion of Wetlands" and "Coastal Engineering Structures.") Mangrove accretion is set to 7mm/year based on Cahoon et al. 1999.

Category 10: Estuarine Beach (Estuarine intertidal unconsolidated shore sand or beach-bar)

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion are calculated using a default of MLLW as the lower elevation boundary for this category. Estuarine beaches convert to open water if inundated or eroded.

Category 11: Tidal Flat (Estuarine intertidal unconsolidated shore mud/organic or flat)

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion are calculated using Mean Low Water as the lower elevation boundary for this category. (See "Conversion of Wetlands" and "Coastal Engineering Structures.") Note, erosion of tidal flats that are exposed to water is assumed to occur at all times, regardless of the extent of wave setup.

Category 12: Ocean Beach (Marine intertidal unconsolidated shore sand)

Elevations are adjusted for sea level rise using equation **(9)**. Unless "Protect All" has been selected beach erosion takes place. Beach erosion is modeled using a relationship reported by Bruun whereby recession is 100 times the relative change in sea level:

$$Recession = 100 \cdot SLRise \tag{22}$$

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:

$$Erosion_{Cell} = Recession - Distance \tag{23}$$

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

$$Fraclost_{OceanBeach} = \frac{Erosion_{Cell}}{Width_{OceanBeach,Cell}} \tag{24}$$

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 ocean beach is adjacent to open ocean, a check for the conditions that lead to overwash is performed (see "Overwash" above).

Ocean beach is also subject to inundation using MLLW as the default lower elevation boundary.

Category 13: Ocean Flat (Marine intertidal unconsolidated shore mud or organic)

This category tends to occur along low energy coastlines. Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion to open water are calculated using Mean Low Water as the default lower elevation boundary for this category.

Category 14: Rocky Intertidal (Marine intertidal rocky shore)

Elevations are adjusted with equation **(9)** (i.e. no sedimentation for this category). Inundation to open ocean is calculated based on the slope of the cell using a default minimum category elevation of Mean Lower Low Water **(19)**.

Category 15: Inland Open Water (Riverine, Lacustrine, and Palustrine open water)
Category 16: Riverine Tidal Open Water

For these two categories, elevations are adjusted for sea level rise using equation **(9)**. If the minimum elevation is lower than the salt boundary and the cell is "adjacent to salt" (within 500 m of salt water or salt marsh) then these categories are converted to estuarine water.

Category 17: Estuarine Water (Estuarine subtidal)

This cell is assumed to rise with sea level, so no elevation adjustment is required.

If there is a clear path of water to the open ocean in the off-shore direction, and the cell is "Adjacent to Ocean" (within 500m of the open ocean), then the cell is converted into open ocean.

Category 18: Tidal Creek (Estuarine intertidal stream bed)

This cell rises with sea level, so no elevation adjustment is required.

No processing is required for these cells.

Category 19: Open Ocean (Marine subtidal)

This cell rises with sea level, so no elevation adjustment is required.

No processing is required for these cells.

Category 20: Irregularly Flooded Marsh (Irregularly Flooded Estuarine Intertidal Emergent)

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion are calculated using the lower elevation boundary for this category (the default is the average of MTL and the salt boundary).

Category 21: Not Used (was "Tall Spartina")

Category 22: Inland Shore (Shoreline not subject to the elevation pre-processor)

Elevations are adjusted with equation **(9)** (i.e. no sedimentation for this category). Inundation to open ocean is calculated based on the slope of the cell using a default minimum category elevation of Mean Lower Low Water **(19)**.

Category 23: Tidal Swamp (Tidally influenced Swamp.)

The elevation of the swamp is adjusted for sea level rise **(8)**. As is the case for all swamp and marsh categories, accretion is added unless the swamp is protected by a dike in which case accretion is assumed to be zero **(9)**.

Version 6: Accretion in the model is hard-wired to 1.1 mm/year based on data taken in GA swamps (Craft et. al, 2008).

If the site is not in an estuary and the lower edge of the swamp is below the salt boundary then the swamp is converted to mangrove (tropical system) or irregularly flooded marsh (non-tropical system) through inundation. If a cell is in an estuary and the lower edge of the swamp is below the salt boundary then the cell category is set using the calculated *FracFresh*.

If erosion is predicted to be heavy (maximum fetch 9 km or greater) then erosion of the swamp will occur **(20)**.

Category 24: Blank (not processed)

Category 25: Vegetated Tidal Flat (site-specific data)

This category is designed to capture high tidal flat that borders on regularly flooded marsh but that has a lower density of vegetation than the adjoining marshland.

Elevations are adjusted with equations **(8)** and **(9)**. Inundation and erosion are calculated using Mean Low Water as the default lower elevation boundary for this category. Vegetated tidal flat converts to water in the event of inundation or erosion. Conversion to tidal flat may be specified on the basis of salinity, however.

Category 26: Backshore (site-specific data)

Backshore is the generally dry part of an active beach and is located above MHHW. Elevations for backshore habitats are first adjusted for sea level rise. If the lower elevation for backshore drops below its minimum elevation then conversion to estuarine beach occurs.

Definitions and Acronyms

Definitions

SLAMM 6.0 Definitions:

- "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)
- "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 Range (GT): Difference between MHHW and MLLW.

To improve clarity, some land-cover and parameter definitions have been updated

- "Inland" tide ranges are no longer relevant as we use "sub-sites" to define changes of tides over a spatial region.
- The "*MHWSpring*" parameter has been redefined as "Salt Elevation." This demarcates the salt boundary-- the boundary between dry lands and saline wetlands. Based on our experience, "salt elevation" may usually be defined as the elevation that is expected to flood at least once per month. This frequency of flooding information is usually available from local NOAA tide gages.
- Brackish Marsh is now referred to as "irregularly flooded marsh" and Salt Marsh has been changed to "regularly flooded marsh" to more closely match NWI designations.
- "Water depth" is no longer a relevant parameter as it is replaced by a model that accepts bathymetry data.

Acronyms

DEM	Digital Elevation Model
IPCC	Intergovernmental Panel on Climate Change
MHHW	Mean Higher High Water
MLLW	Mean Lower Low Water
MTL	Mean Tide Level
NWI	National Wetlands Inventory, from US Fish and Wildlife Service
SLAMM	Sea Level Affecting Marshes Model

Technical Details

Installing SLAMM

- The SLAMM6 Installer may be downloaded from the following site:

http://warrenpinnacle.com/prof/SLAMM6/SLAMM6.exe

The installer will create SLAMM6 files or SLAMM6 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_Open_Source.zip

Note, this code requires Delphi 2007 or later to compile. Also, an additional open-source third party library called the Delphi OpenGL is required. That website is down, hopefully only temporarily. In the short run, users may comment out the OpenGL portion of the code or bring in an alternative OpenGL library for Delphi. If the latter task occurs, we'd appreciate a sharing of the source code.

The source code will eventually be updated using an SVN subversion client. We use Tortoise SVN to develop the code but haven't put that repository on-line at this time.

Command Line Option

To automatically run a SLAMM simulation save an existing SLAMM6 file as "txt" rather than the "SLAMM6" file-type. (If you look at that file you will see 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 (NED). (units are degrees)
- DEM Data: Digital elevation map data. Typically inappropriate to use for calculating sea level rise effects but serve as data in areas where NWI data are not available. (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.
- Dike Data: Boolean, 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 coops database.

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 (maximum fetch of 9km) has been exceeded prior to the incidence of horizontal erosion.

Producing Data Files

Raster files should 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. http://ned.usgs.gov/

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 latest database of SLAMM codes to
- 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 the table presented below
- 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.

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."

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

NWI to SLAMM Category Conversion

The tables provided below do 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.

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).

Table 4: NWI Classes to SLAMM 6 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 4 (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

DATE 1/14/12010

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, Dick, Swords, and Wilen 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
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 2 2 2 11 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 17 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 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 . . .
```

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