Application of Sea Level Affecting Marshes Model (SLAMM) to the Georgia Coastline

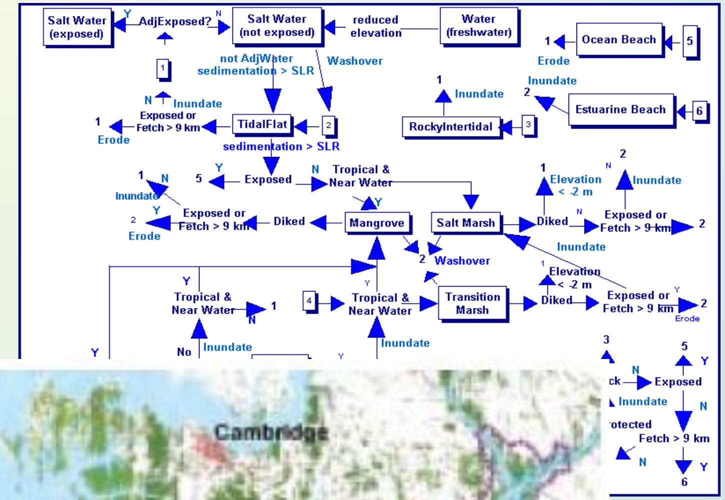
Jonathan S. Clough

At the invitation of Georgia Department of Natural Resources
SKIO library, Skidaway Island

November 28, 2012

What is SLAMM?

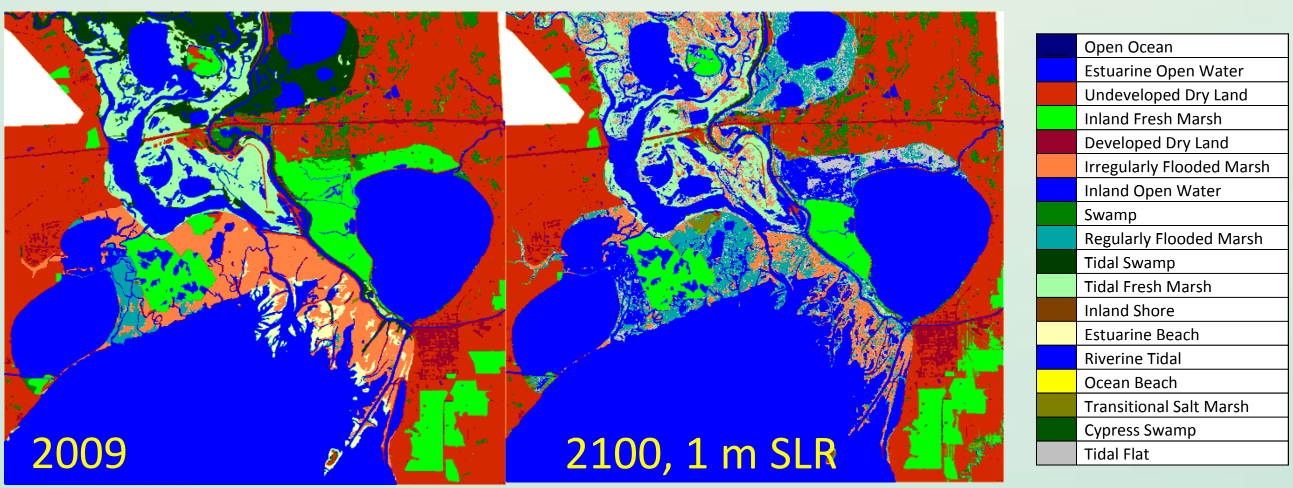
- A Complex Decision Tree Incorporating Geometric and Qualitative Relationships is Used to Represent Transfers among Coastal Classes
- Provides Map-based Outputs (as well as Quantitative Figures)



Blackwater National Wildlife Refuge: Year 2100 (27.2 inches)

Sea Level Affecting Marshes Model (SLAMM)

- Can provide numerical and map-based output with minimal computational time
- Modest data requirements allow application to many sites at a reasonable cost
- Applied to more than 120 National Wildlife Refuges, Southern Louisiana, Coastal Georgia, South Carolina Puget Sound, Oregon Coast, etc.

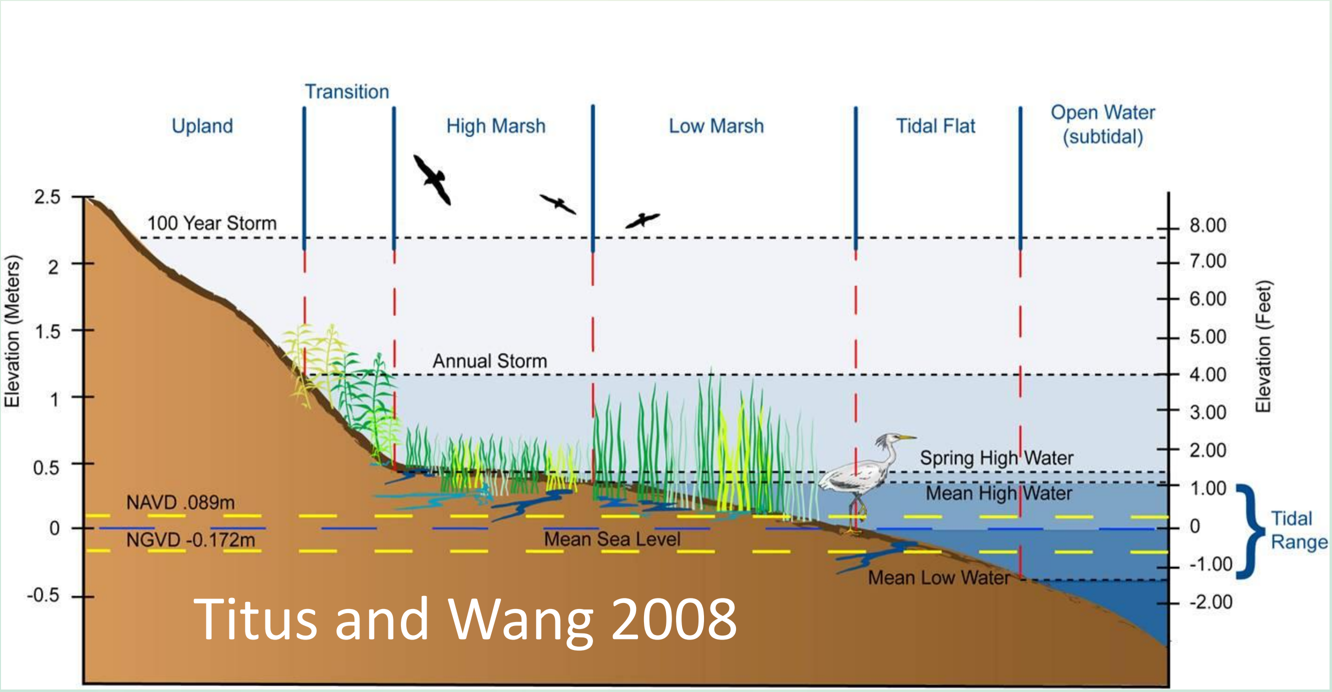


Model Development Highlights

- SLAMM was Developed with EPA Funding by Dr. Richard A. Park (Park et al. 1986)
- SLAMM 2 was Used to Simulate 20% of the Coast of the Contiguous U.S. for the 1991 EPA Report to Congress (Peer Review, Model Validation using LA Coast)
- Three Year EPA STAR Grant (2005-2008) Provided Funds for Significant Model Development (SLAMM5)
- U.S. FWS Funding for Refuge Simulations (Ongoing)
- GOMA / TNC Funding of Two Gulf of Mexico Simulations (2009)
- Code and Model are Open Source

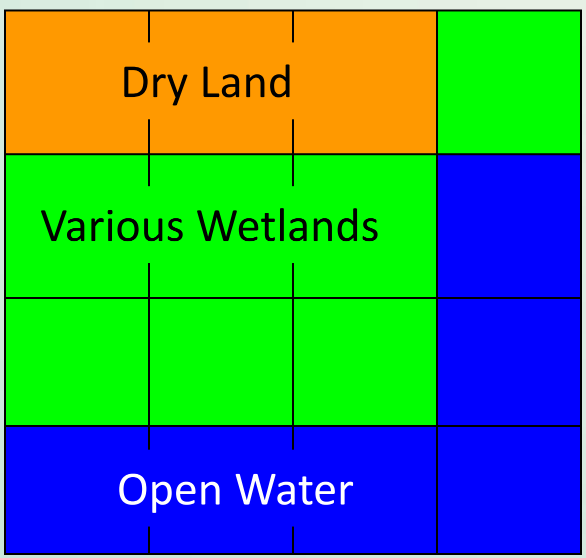
Model Process Overview

Addresses Six Primary Processes (Inundation, Erosion, Saturation, Overwash, Accretion, Salinity)

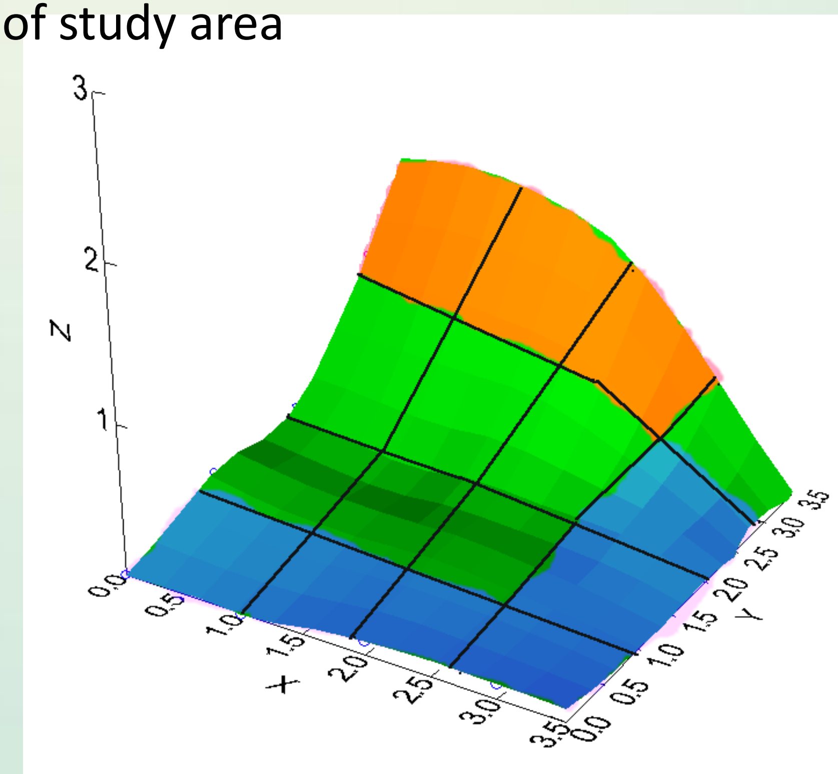


Conceptual Model

- Square “raster” cells with elevation, slope, aspect, estimated salinity, wetland type
  - Cells may contain multiple land-types
  - Cell size flexible given size of study area



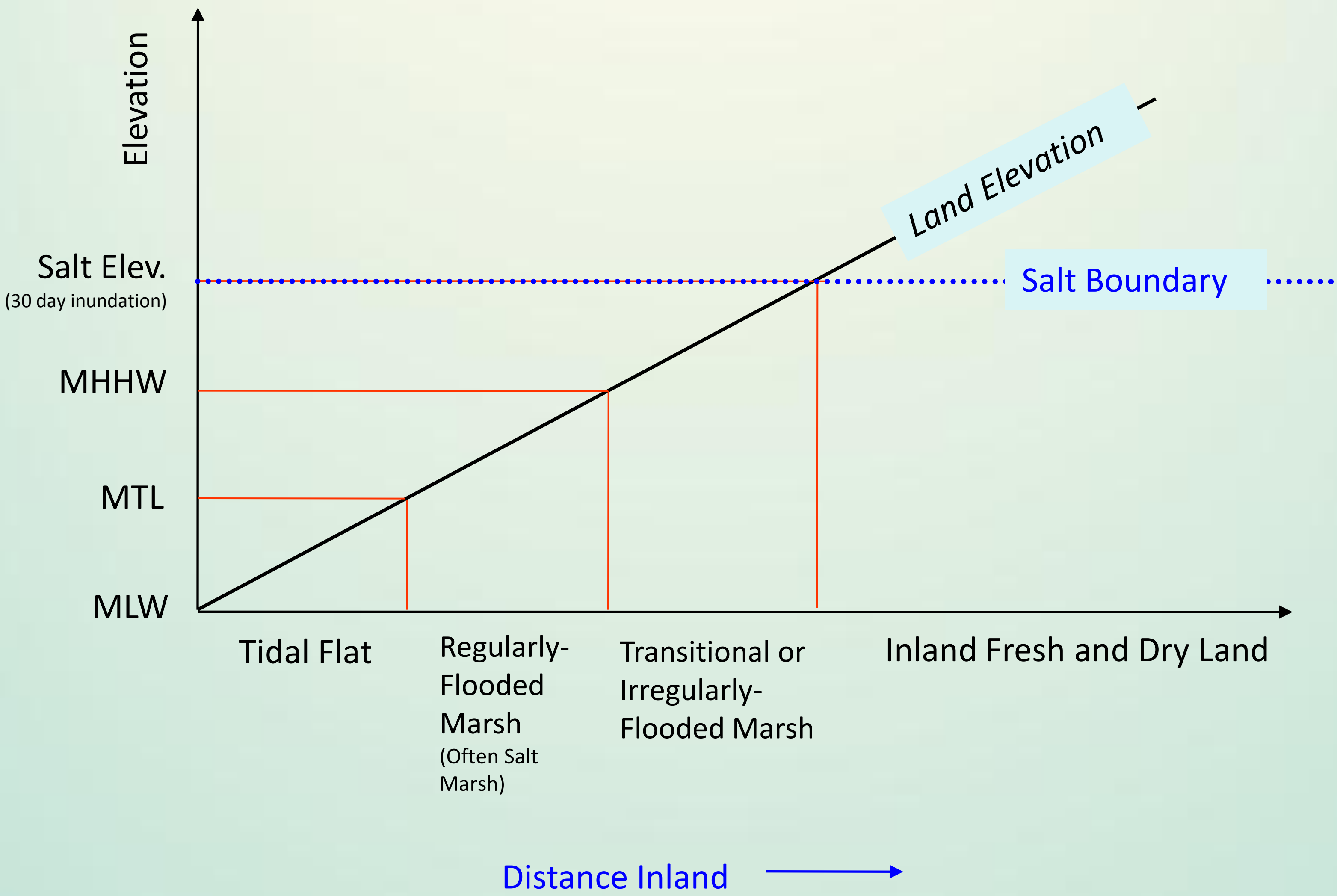
2D Representation



3D Representation

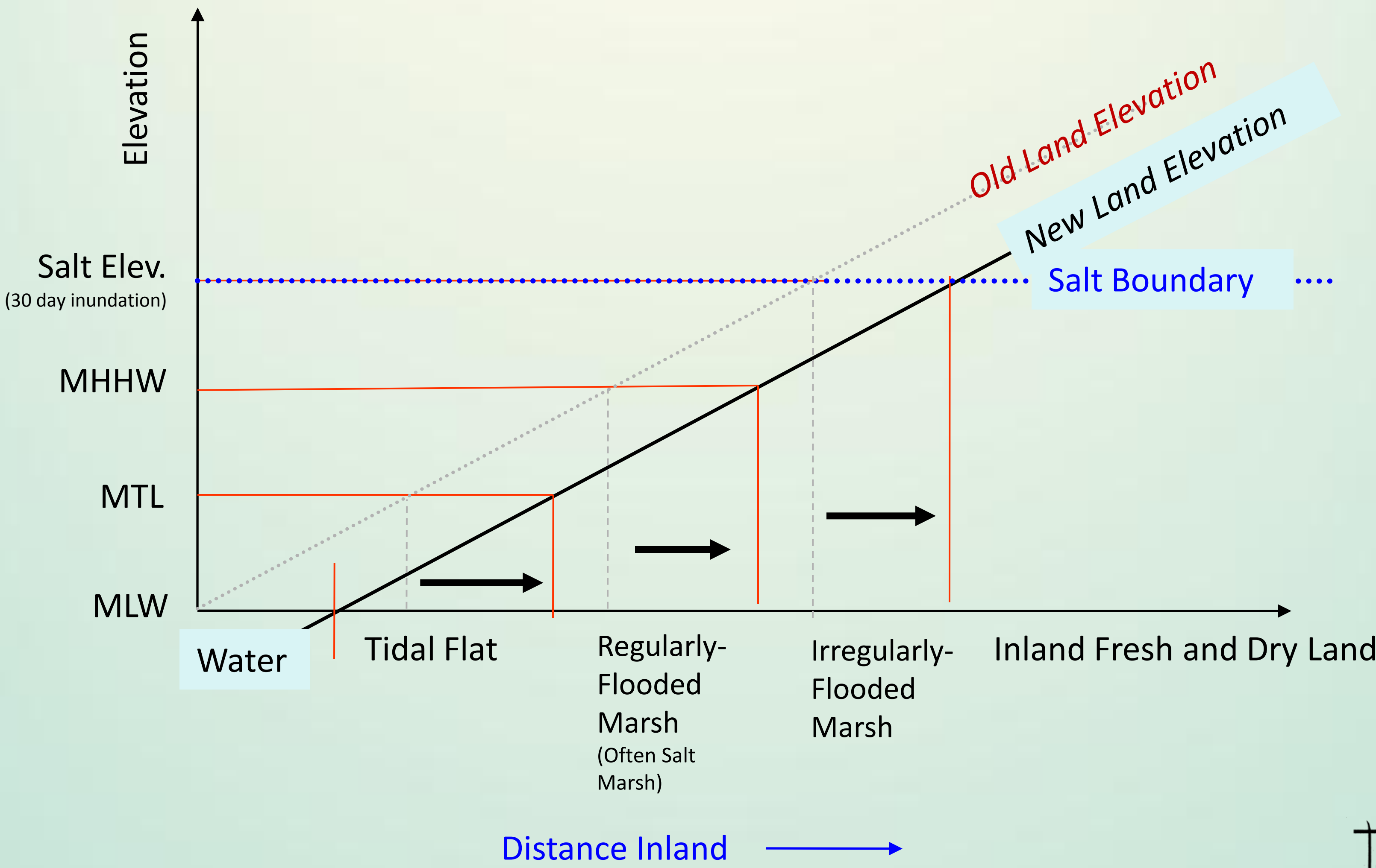
SLAMM Inundation Model

Equilibrium Approach

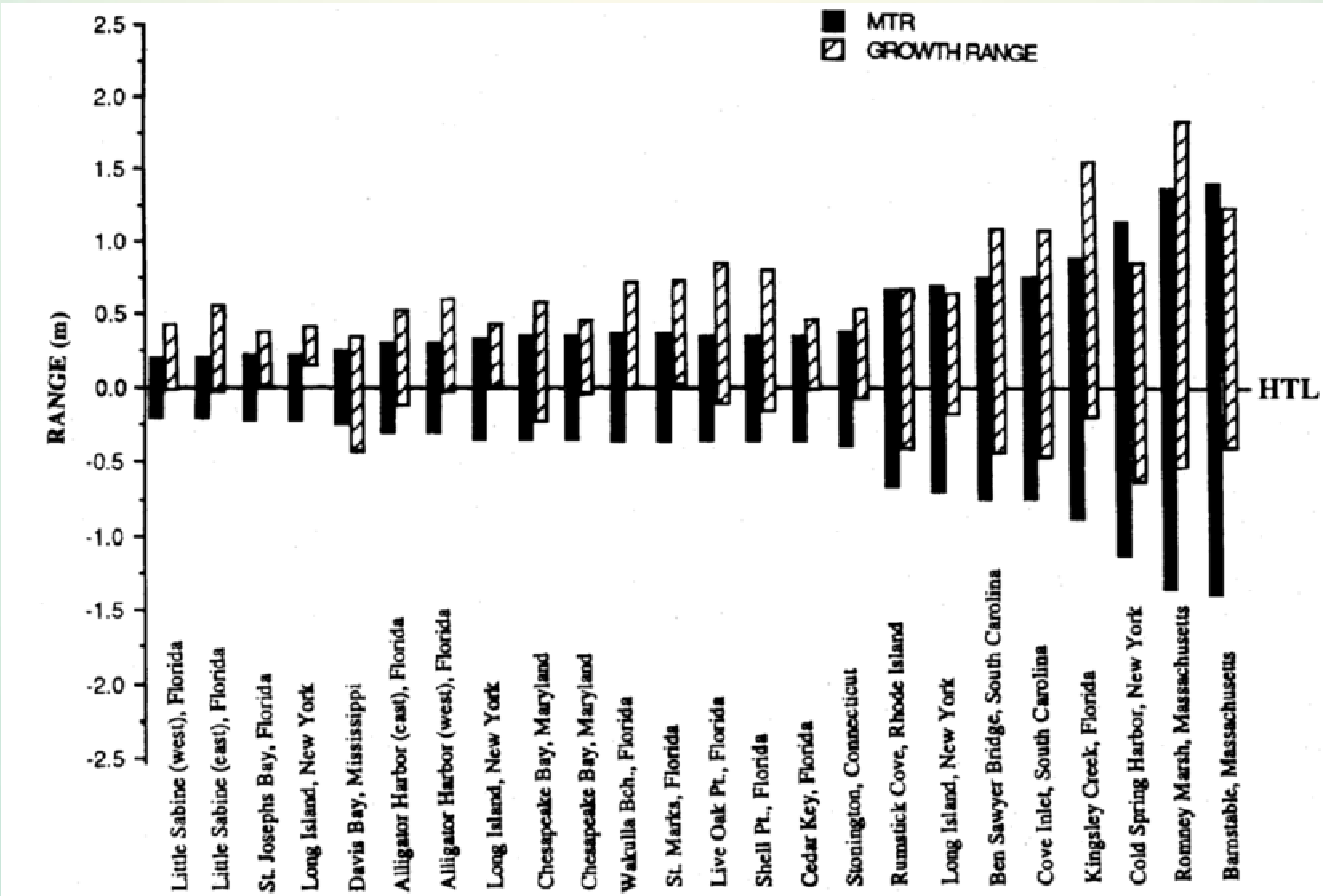


SLAMM Inundation Model

(Migration of Wetlands Boundaries due to Sea Level Rise)



Salt Marsh by Elevation



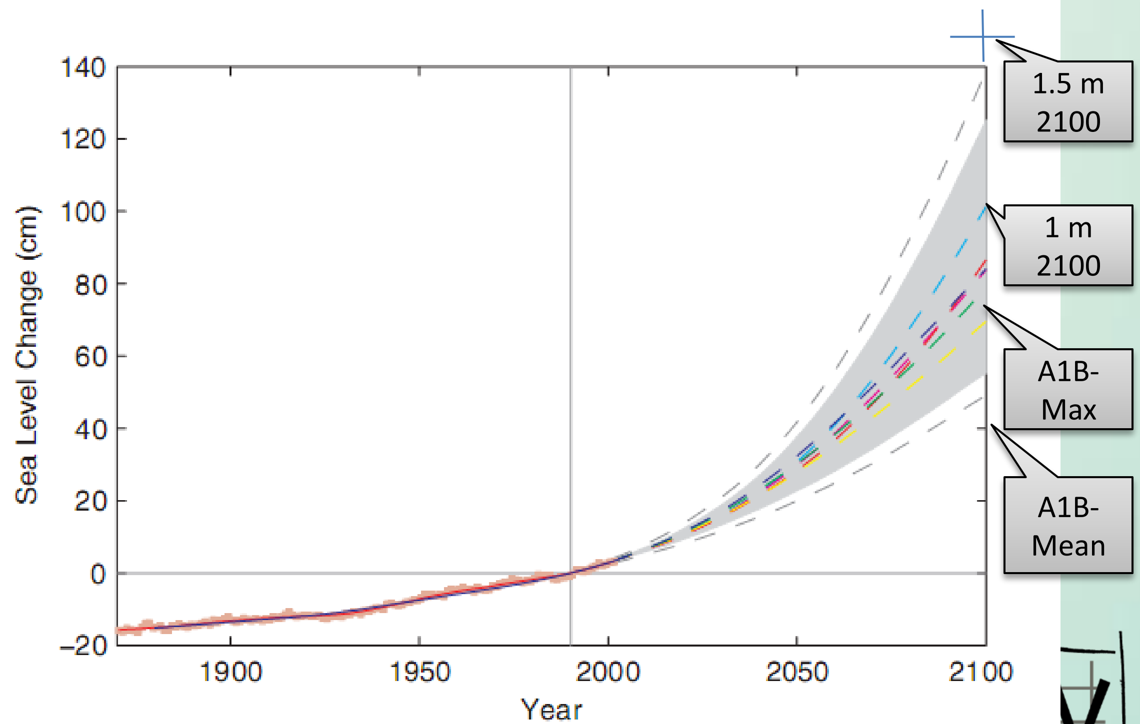
Source McKee & Patrick, *Estuaries*, Vol. 11, No. 3, 143-151, 1988.

Sea Level Rise Scenarios

- Model runs within the range of feasible SLR scenarios (generally 0.4 to 1.5 meters of Eustatic SLR by 2100)

- Model incorporates IPCC Projections as well as higher rates of SLR

- Global (Eustatic) Rates of SLR usually corrected for local effects using long-term tide gauge trends or uplift data



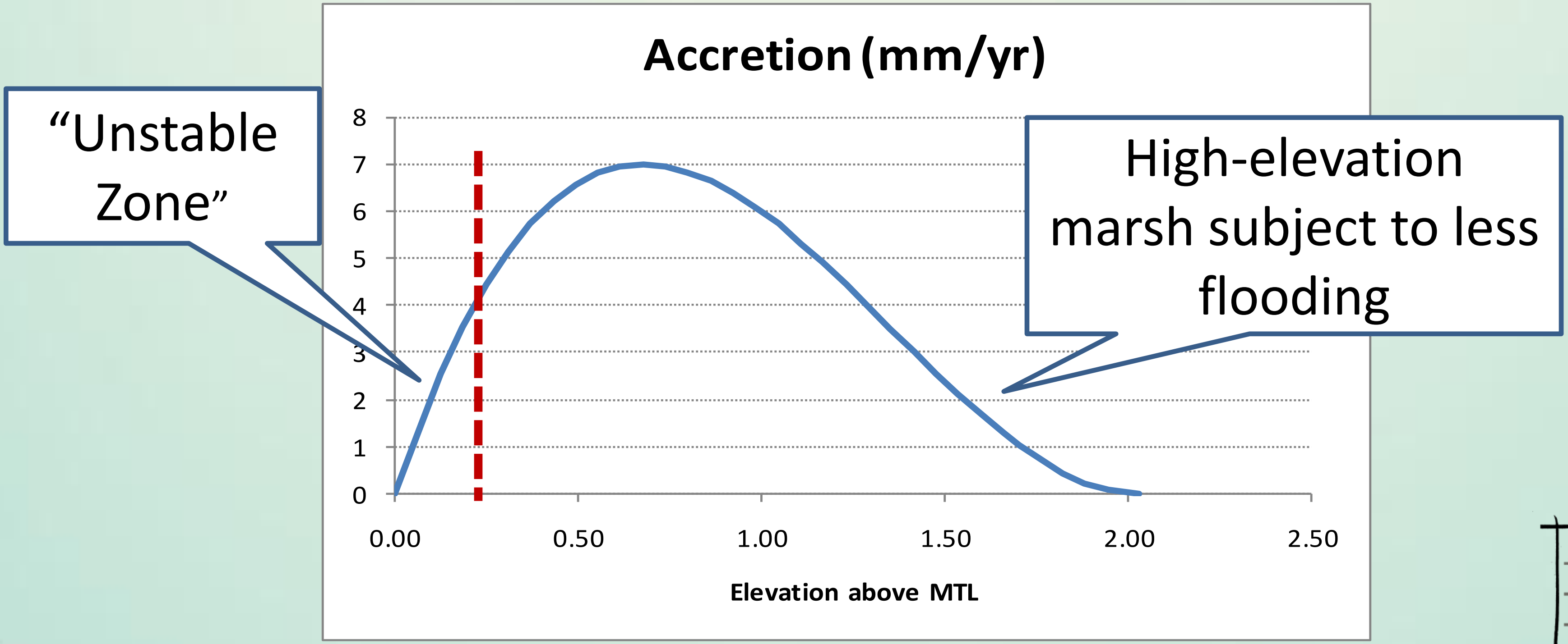
Source Rahmstorf, *Science* 2007

Fate of Wetland Cells

- Adjust cell elevation based on SLR, Accretion, Uplift / Subsidence
- Determine if cell has fallen below minimum elevation
- If cell is in defined estuary, determine type based on salinity
- If cell is exposed to water and meets maximum fetch, erode cell

Feedbacks to Accretion

- SLAMM 6 Allows for Elevation Feedbacks to Accretion as shown by Morris et al. (2002)
- Model is very flexible; optional



Connectivity Component

- Method of Poulter & Halpin 2007
- Assesses whether land barriers or roads prevent saline inundation
- Can be used for levee overtop model with fine-scale DEM

Simple Erosion Module

- Model applies observed historical erosion rate on top of inundation effects.
  - Usually average not site-specific erosion
- Optional Bruun Rule for Ocean Beaches
  - Generally not used in contemporary applications
- Maximum wave fetch for marshes
  - Maximum Fetch calculated at each cell based on previous land-changes.
  - When threshold of 9km is exceeded horizontal erosion rates are implemented

Beach & Tidal Flat Modeling

- Ocean/Tidal Flat to Water Interface is Uncertain
  - Land-cover and Elevation Data often not tidally coordinated
- Erosion is Ephemeral
- Sedimentation Rates Highly Variable
- No Sediment Budget in the model
  - Once the Tidal Flat is below MLLW it's gone
  - Does not model dynamic effects if spit lost
- Substrate not considered

Dike Considerations

- Traditional SLAMM has “on-off” dike layer
  - Option to model dike elevations
- “Muted” tidal regions are handled by reducing tide-ranges
  - This tide range remains constant, however
- Connectivity can be used to calculate dike overtop but subject to elevation error.
- Dike Removal
  - Dynamic accretion processes following dike removal are not represented

Additional Complications

- Subsidence & Isostatic Rebound
  - Spatial maps added, but constant over time
- Barrier Islands Overwash
  - “One-size-fits-all” model
- VDATUM Integration
- Developed Land Effects

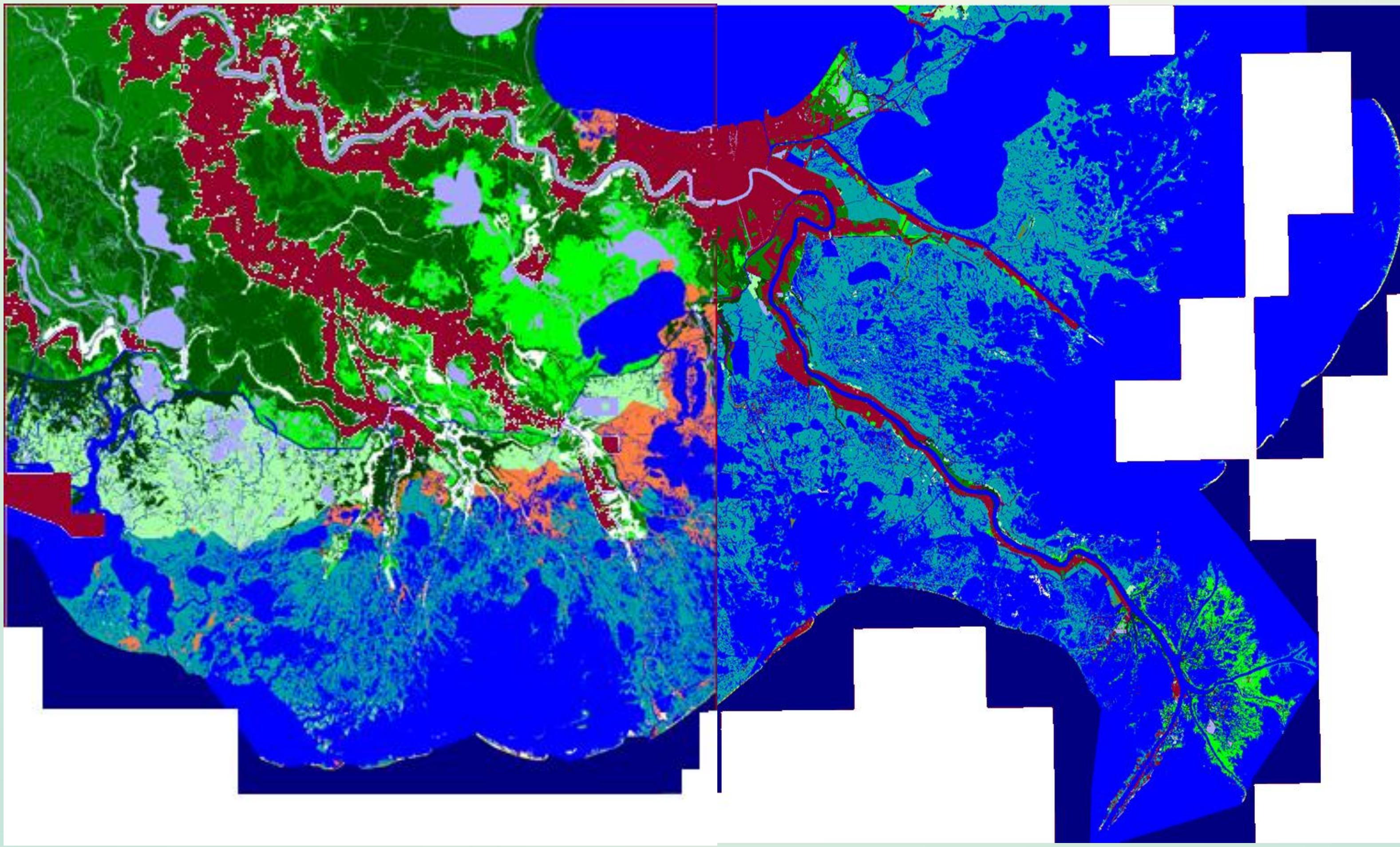
- Dynamic Changes in Tide Ranges
- Changes in Storm Event Regime
  - SLAMM is not a storm surge model

“Hindcasting” Capability

- Run the model with historical data for validation and calibration
- Results will be imperfect
  - Historical elevation data with high vertical resolution unavailable
  - Historical land-cover data are spotty and changes in NWI classification have occurred
  - Model will not predict land-use changes, beach nourishment or shoreline armoring
- For many sites, hindcasting is not possible due to insignificant RSLR “signal”
- In GOM, land subsidence amplifies SLR signal enough to make hindcasting possible

SLAMM Louisiana Study Area

- 15 Meter Cells, 39 Thousand Square KM



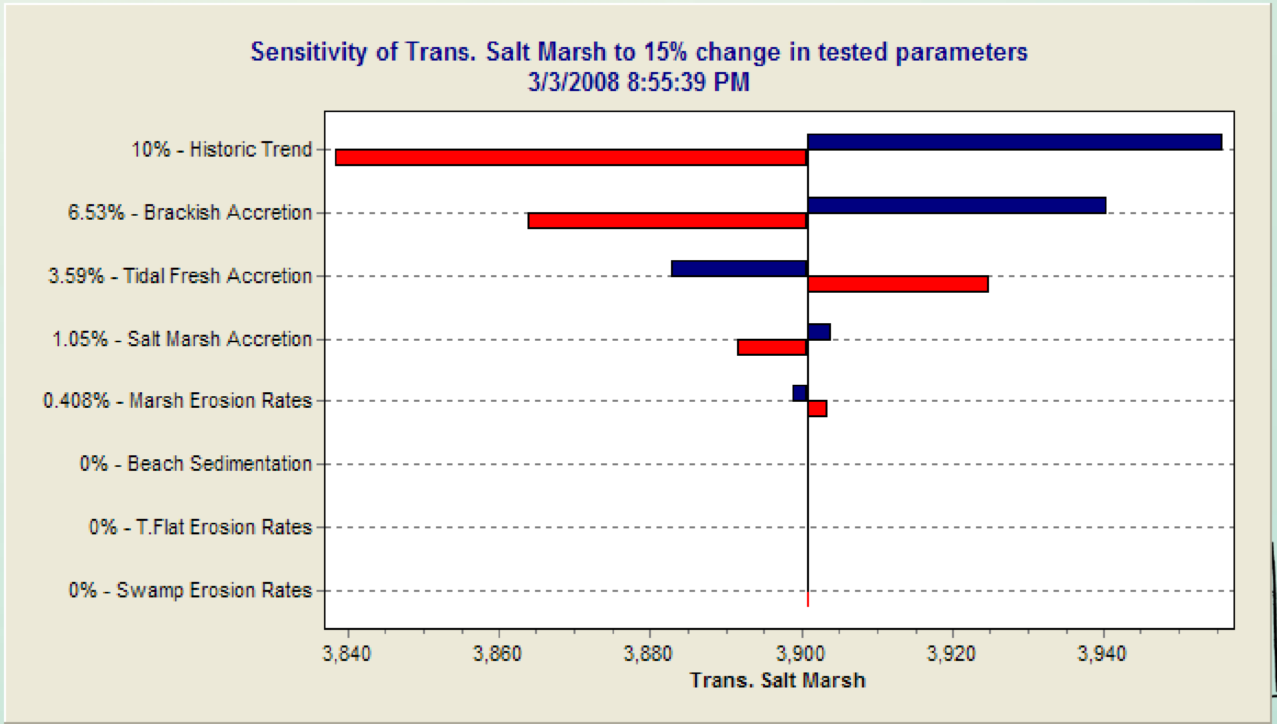
Glick et al., 2013, Potential Effects of Sea-level Rise on Coastal Wetlands in Southeastern Louisiana, *JCR,*

Table 5. *Hindcast results. Percentage of land cover lost between 1979 and 2007 as predicted and observed. Salt Marsh category includes regularly and irregularly-flooded marsh; Fresh Marsh includes inland and tidal fresh marsh; Swamp includes swamp and cypress swamp.*

Land cover type	WEST		EAST		TOTAL	
	Predicted	Observed	Predicted	Observed	Predicted	Observed
Salt Marsh	12%	19%	33%	28%	25%	25%
Fresh Marsh	41%	44%	63%	79%	49%	57%
Total Marsh	28%	33%	43%	44%	35%	39%
Swamp	41%	13%	60%	56%	46%	24%
Beach	99%	56%	94%	84%	96%	76%

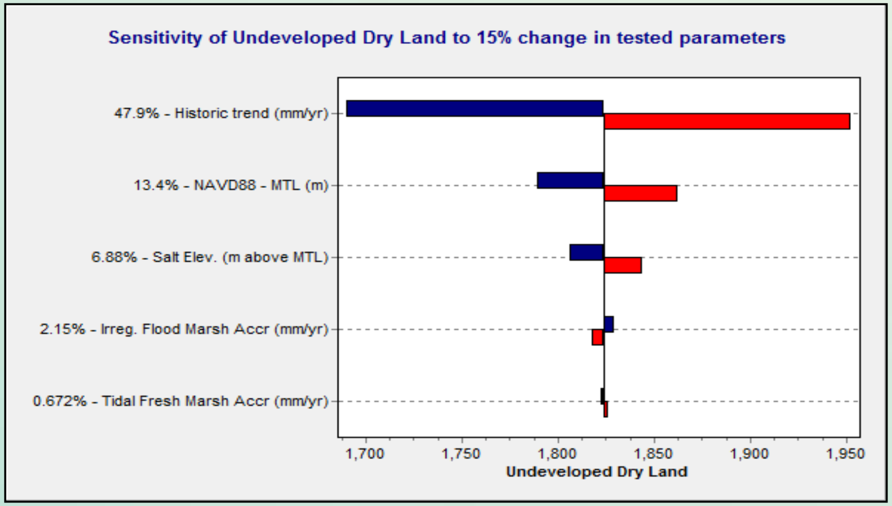
Sensitivity Analysis

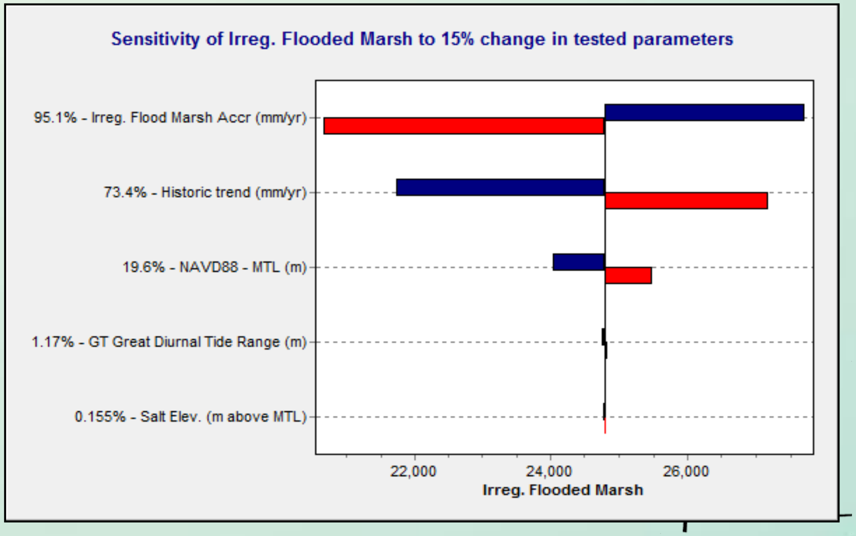
- "Sensitivity" is the variation in output of a mathematical model with respect to changes in the model inputs (Saltelli, 2001).
- Sensitivity analysis ranks model input assumptions with respect to their relative contribution to model output variability or uncertainty (EPA, 1997).
- Tornado Diagram:



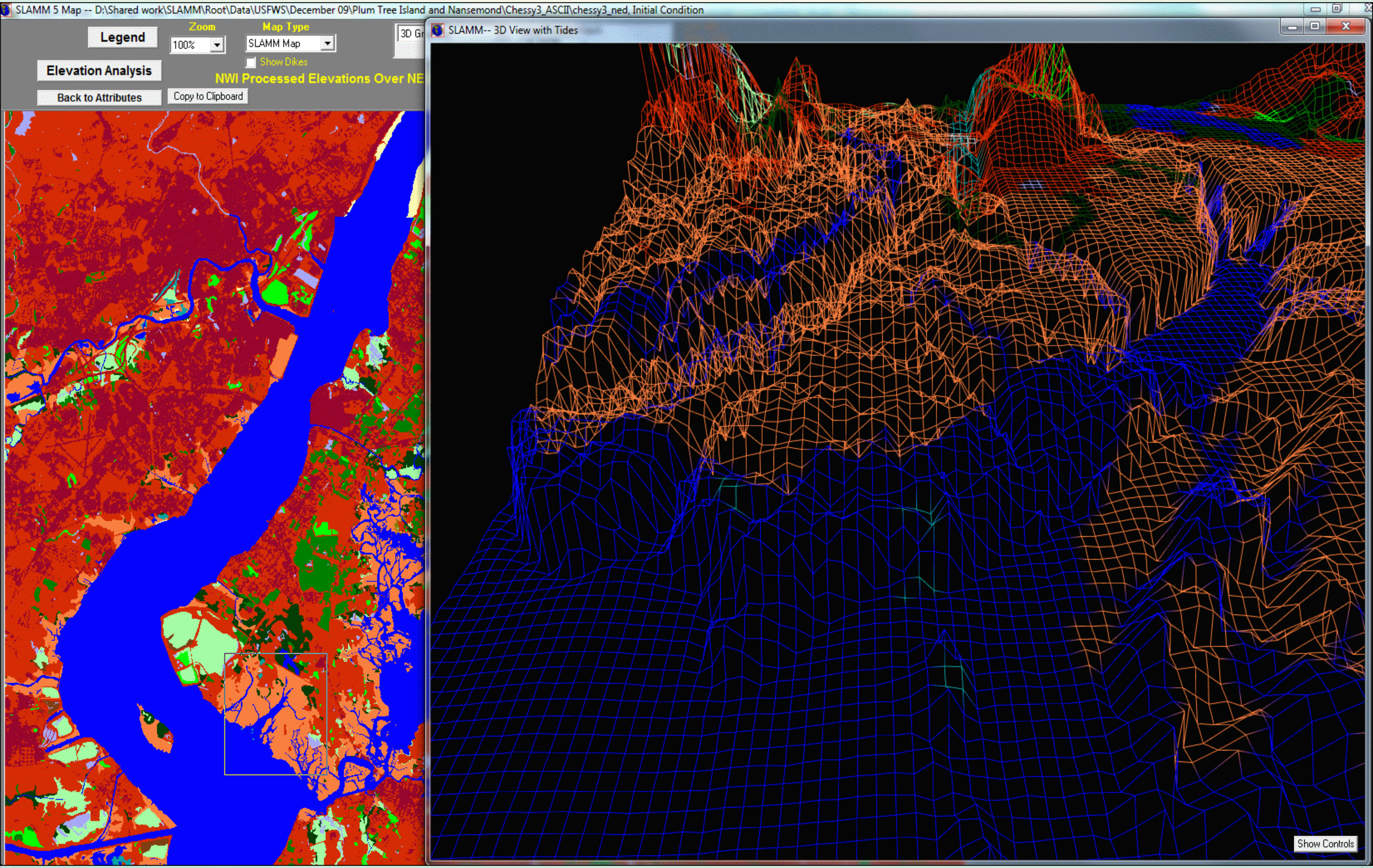
Sensitivity Analyses in GOM– Lessons Learned

- Marshes most sensitive to accretion rates
- Beaches and Tidal flats most sensitive to parameters that affect SLR rates, tide ranges, and initial condition elevations
- Dry land most sensitive to SLR rates.





3D Visualizations



Uncertainty Module Addresses Two Primary Criticisms

- Accretion Model
  - Doesn’t account for feedbacks (not true in SLAMM 6)
  - Manner in which feedbacks are accounted for is uncertain

- Lack of uncertainty evaluation
  - How confident are you of the results?
  - Interpretation of deterministic results difficult
  - What to do if available input parameters are not very good?
  - Decision making difficult since likelihood and outcome variability are unknown

Model prediction uncertainties

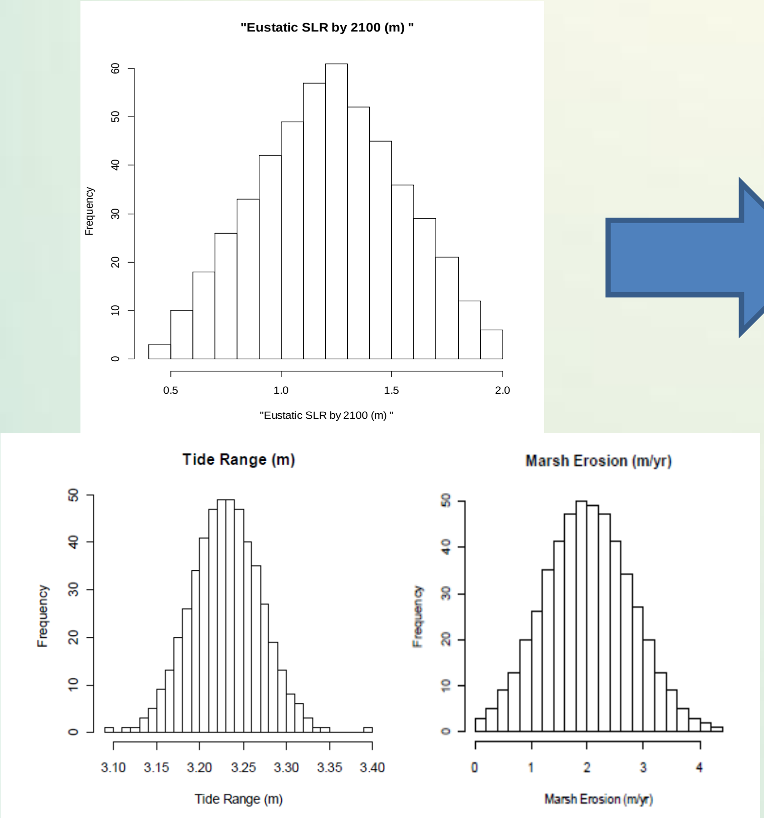
- SLAMM predictions are always affected by uncertainties

Inputs affected by uncertainty and data errors:

- Sea Level Rise
- Uplift / Subsidence
- Tide ranges
- Height of salt-water
- Overwash Parameters
- Elevations
  - LiDAR and NAVD88 Corr.
- Accretion Rates
  - Extent of Feedbacks
- Erosion Rates

- Therefore, there is not *one* prediction that is right, but rather *a distribution* of possible future wetland coverages

Parametric Model Input Distributions



Model Output Distributions

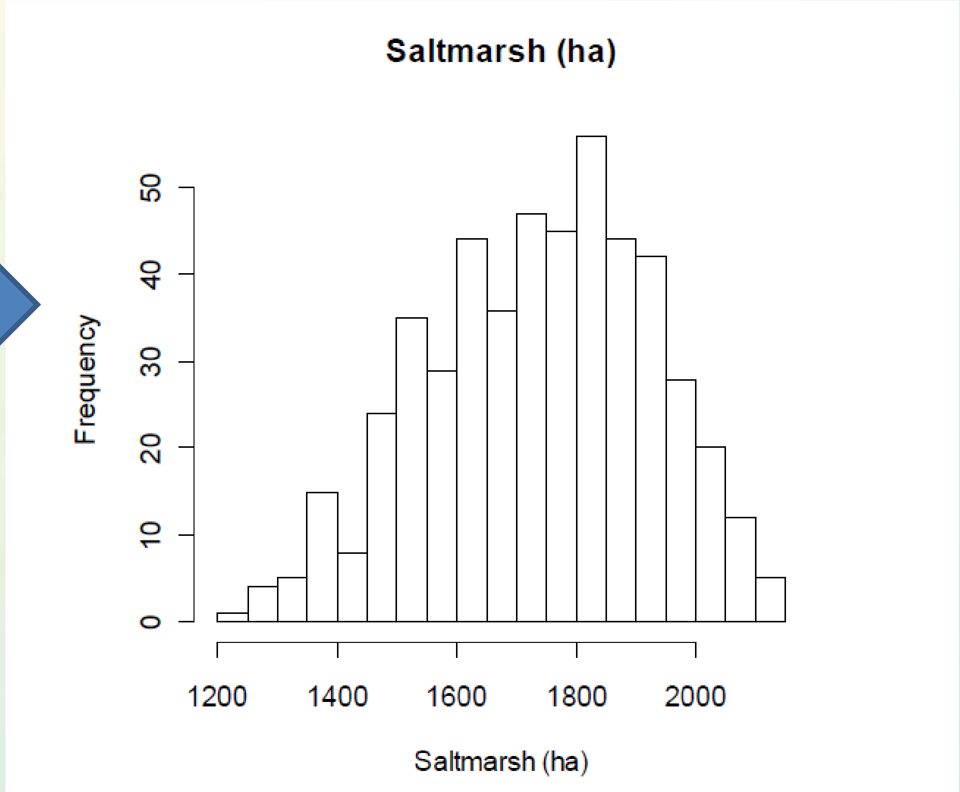
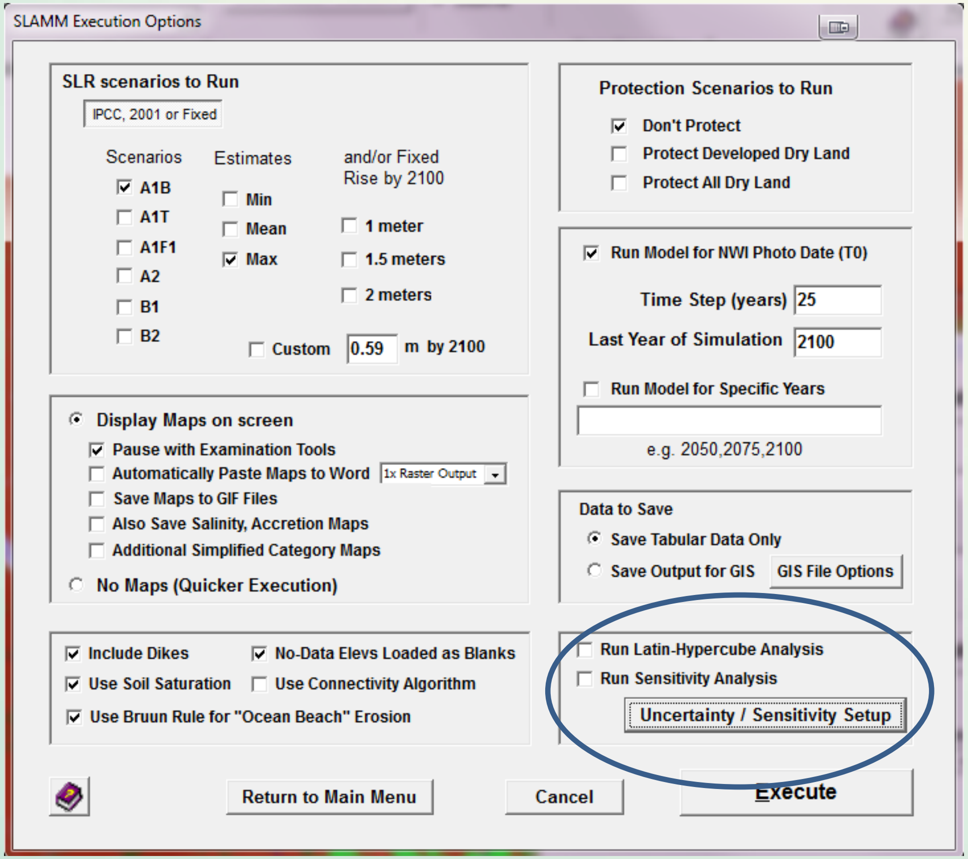


Figure 28: Salt Marsh in 2100 over 500 iterations

Examining SLAMM results as distributions can improve the decision making process

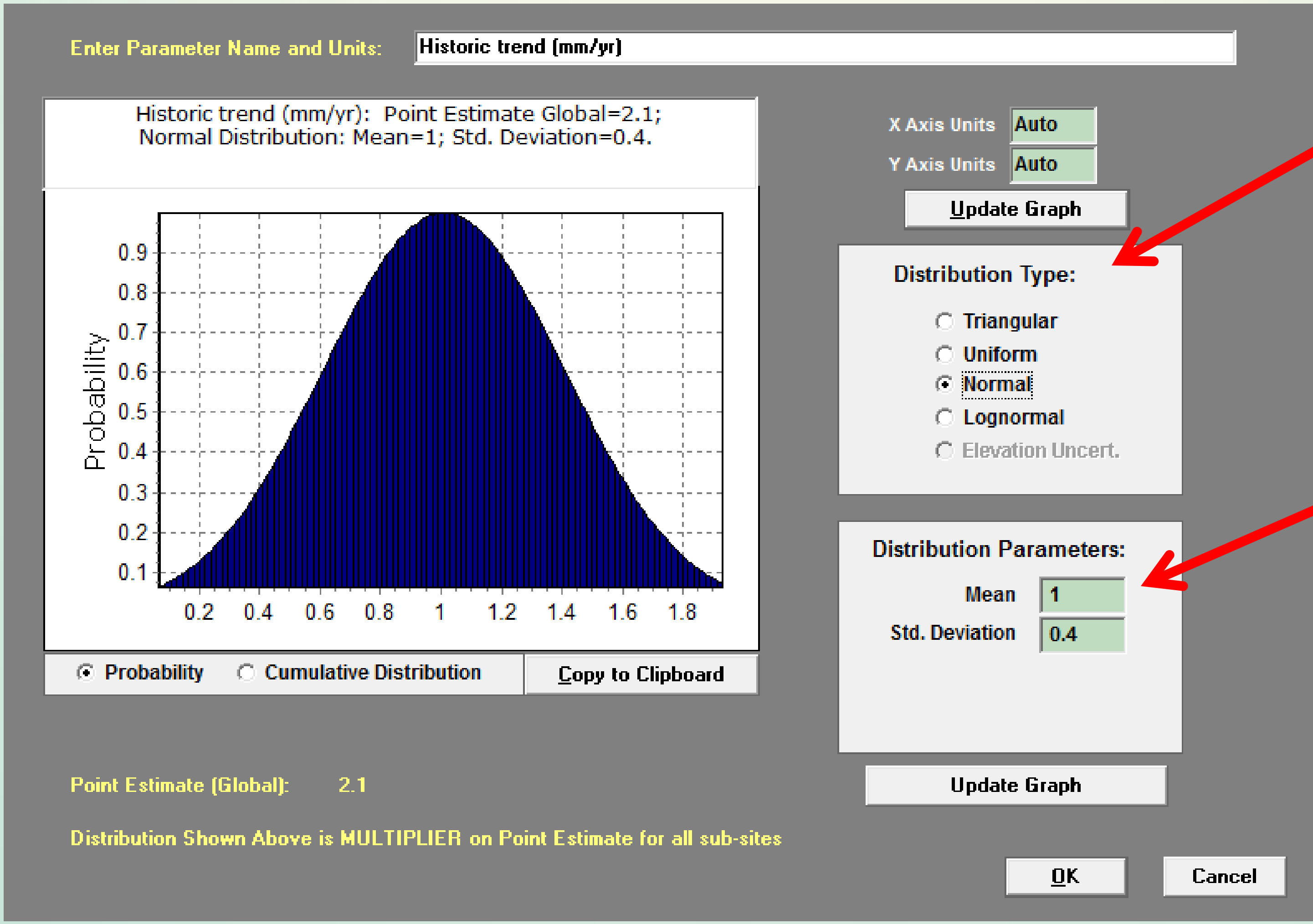
- Results account for parametric uncertainties
- Range of possible outcomes and their likelihood
- Robustness of deterministic results may be evaluated

SLAMM Uncertainty Analysis Module



- Initial development of SLAMM Uncertainty Analysis **funded by Ducks Unlimited**
- SLAMM 6.1 beta complete, technical documentation under development
- Monte Carlo Uncertainty Analysis fully built into SLAMM interface
- Latin-Hypercube stratified sampling designed for efficiency (reduces iterations to convergence)

Parameter uncertainty input distributions

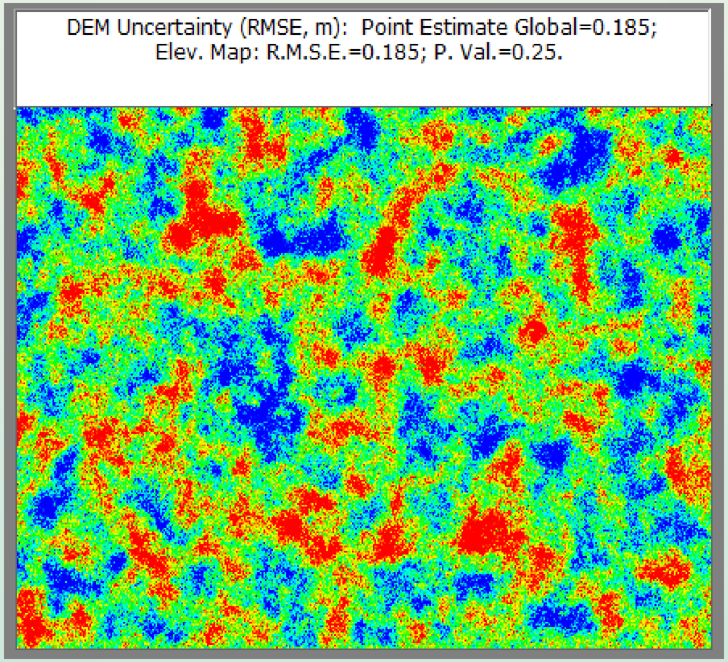


All parameters may be represented as distributions

Multipliers used to retain subsite individuality

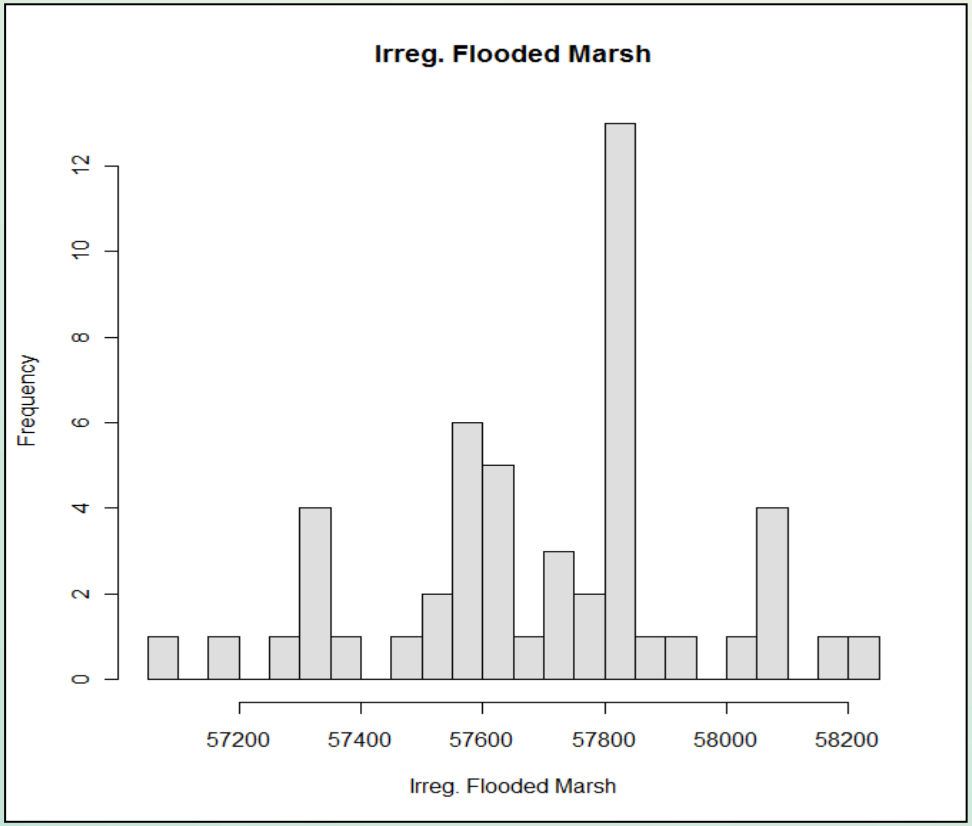
SLAMM Elevation Uncertainty

- Elevation, MTL correction
- Creates a set of unique, equally likely input maps for each simulated scenario on the basis of elevation data uncertainty statistics
  - Root mean squared error (RMSE) from LiDAR metadata
- Spatial Autocorrelation
  - high error zones tend to cluster together



GOM, Elevation Data Uncertainty – Lessons Learned

- Error from LiDAR data is not a particularly important part of overall model uncertainty

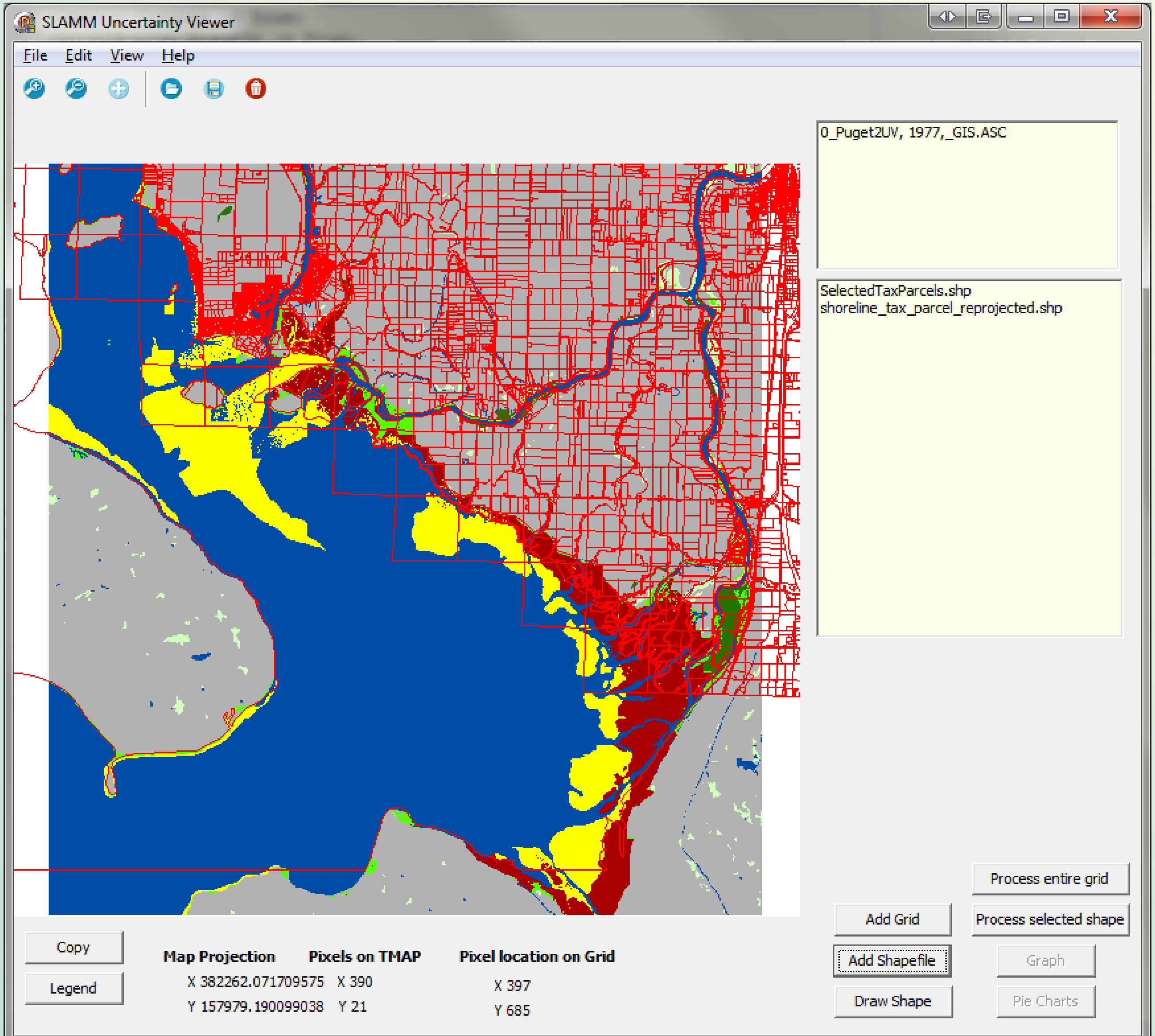


Irregularly-flooded marsh initial condition was 76,500 acres

uncertainty in model predictions produced by elevation data errors range from loss rates of

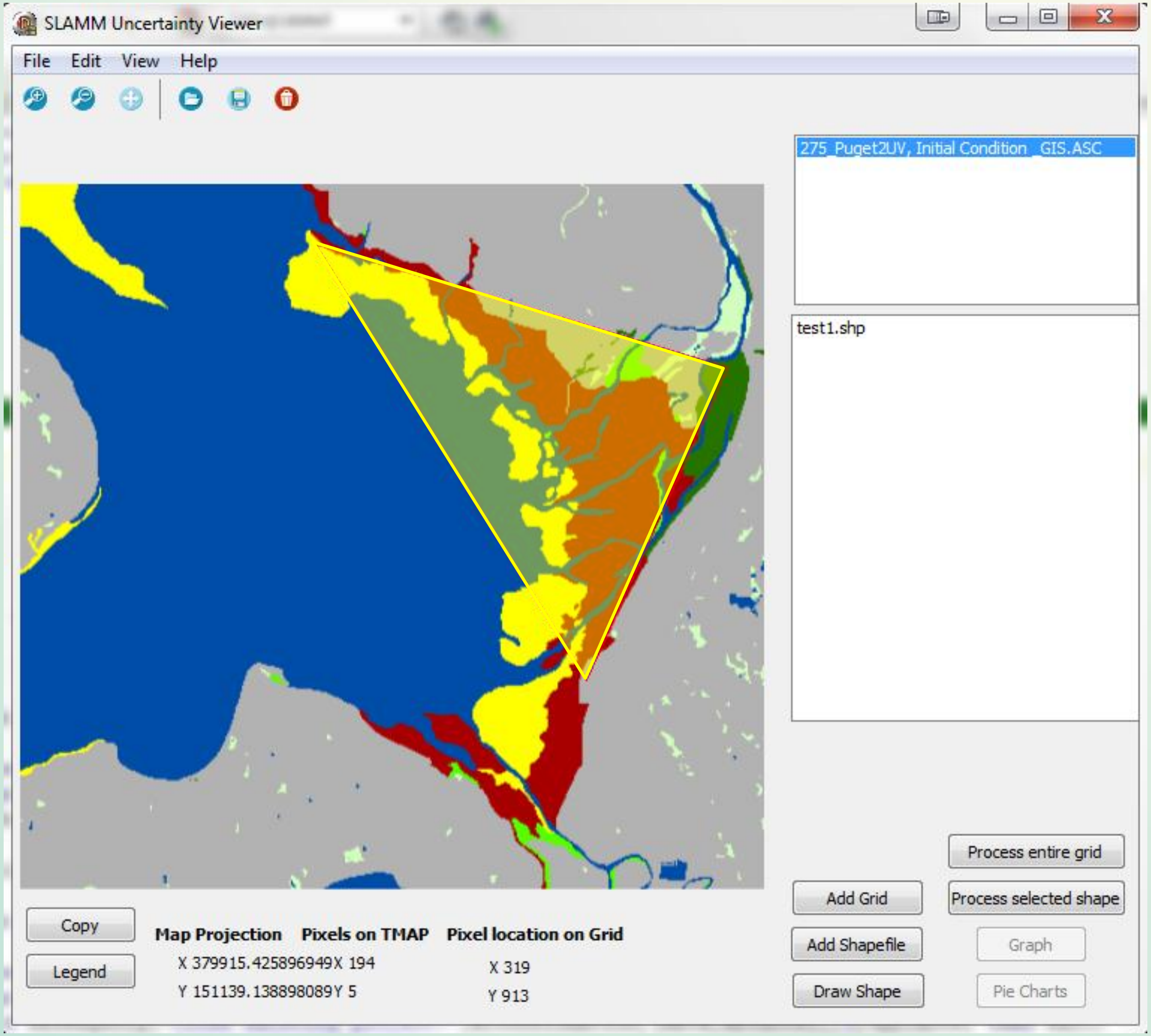
23.8% to 25.4%.

SLAMM Uncertainty Viewer



- Designed by Ducks Unlimited
- Processes completed SLAMM uncertainty runs
- Graphical representation of results
- Integration with GIS Layers

SLAMM Uncertainty Viewer

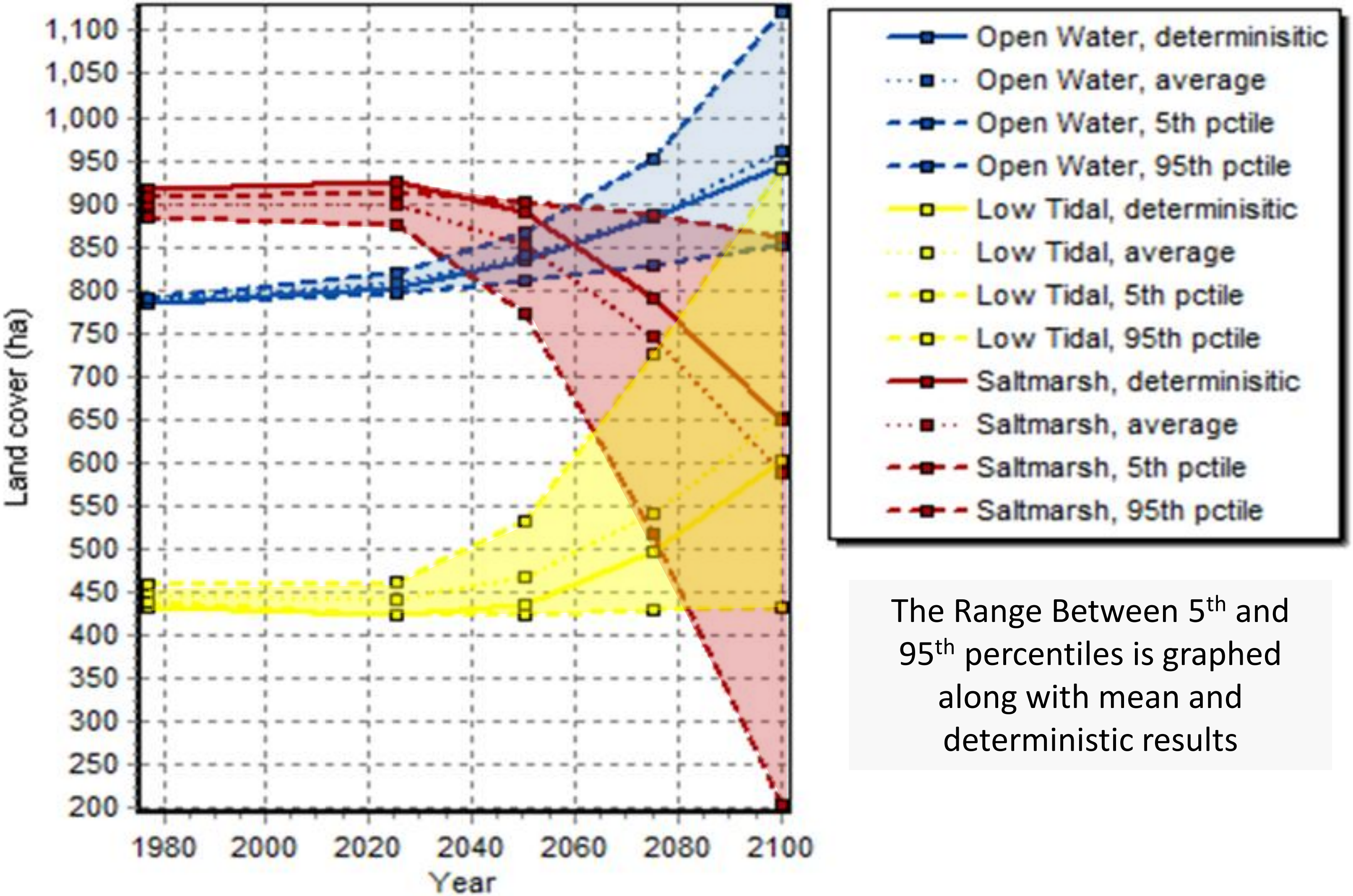


- SLAMM Uncertainty results are integrated with GIS layers
- User can process the entire study area as well as a user specified area for:
  - *Land acquisition*
  - *local interests or projects*
- Polygons defining the area of interest can be *imported from GIS* or *drawn* by the user

SLAMM Uncertainty Viewer

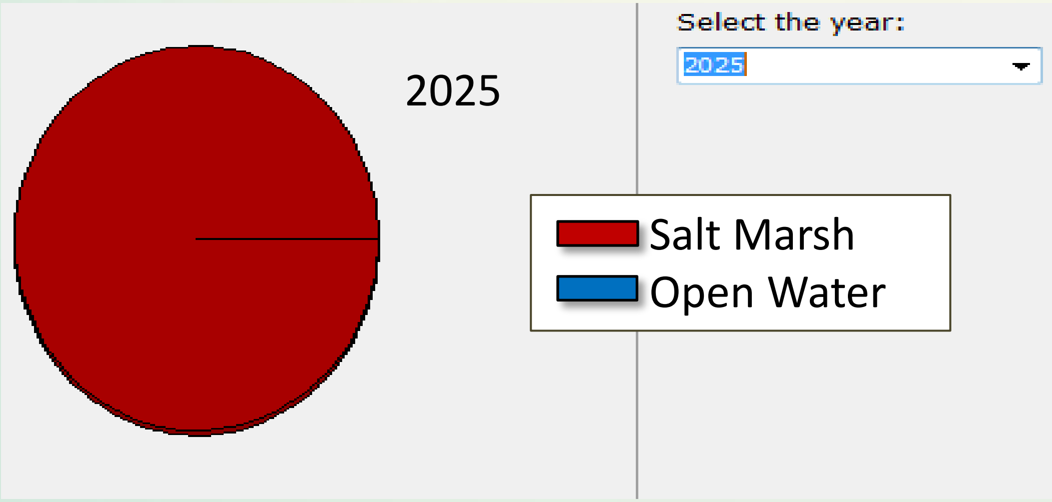
Input parameter uncertainties can lead over time to different wetland coverage

"Uncertainty Cloud" for Selected Region



The Range Between 5th and 95th percentiles is graphed along with mean and deterministic results

SLAMM Uncertainty Viewer

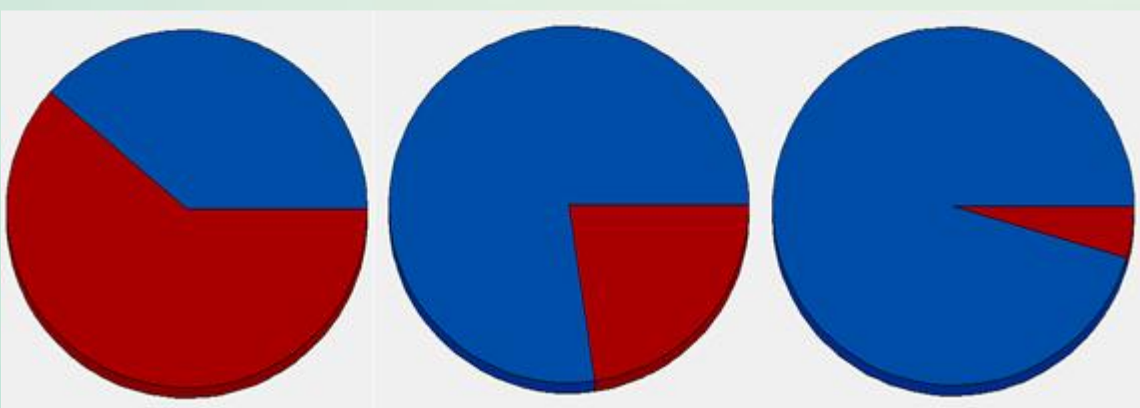


A pie-chart is also available to present uncertainty in the dominant land cover type (for the selected region) over time

In this example, in 2025 the major land cover of the area is predicted to be saltmarsh no matter the input parameters.

In 2050, 60% of the simulated scenarios still predict saltmarsh as the major land cover type but 40% simulations predict open water as the major type.

2050 2075 2100



By 2100 95% of the simulations predict open water the major land cover no matter the input parameters

Summary and Perspectives

- **Uncertainty analysis combined with the viewer** simplifies uncertainty output for end-users, analysts and decision makers
  - The effects of input uncertainties, some model uncertainties
  - Robustness of deterministic results
  - Potential outcomes in particular areas that may be interest for land acquisition, etc.
  - Quantitative framework to assist educated decision making
- Development of the tool is an ongoing project
  - Open to feedback from end-users
  - Will soon include other existing analysis tools and calculations:

    For example, cell-by-cell maps showing likelihood of land type change
  - Addition of correlations

Application to Coastal Georgia

- Original application with SLAMM 5
  - Three-year STAR grant
  - Documented in Craft et al., 2009, *Frontiers in Ecology and the Environment*
  - No LiDAR

- 2012 application with SLAMM6
  - Accretion feedbacks utilized with MEM2 model
    - Jim Morris' updated accretion feedback model as applied by Chris Craft's team
  - Salinity model updated and calibrated to data
  - LiDAR data used for entire coastline

SLAMM Strengths

- Open source
- Relatively simple model
- Ease and cost of application
- Relatively quick to run (enables uncertainty analysis)
- Contains all major processes pertinent to wetland fate
- Provides information needed by policymakers

Strengths (cont.)

- Detail oriented flow chart
- Relatively minimal data requirements
- Designed in poor data environment -- has assumptions to work through those conditions.
- Internal uncertainty analysis

SLAMM Model Limitations

- Not a Hydrodynamic Model
  - Conceptual model captures these sites initial conditions well; future changes in hydrodynamics may not be properly represented.
- Spatially Simple Erosion Model
  - Could be modified or replaced with more sophisticated model
  - Beach erosion is ephemeral and difficult to quantify anyway

Model Limitations

- No Mass Balance of Solids
  - i.e. accretion rates not affected by bank sloughing
  - Storms do not mobilize sediment
- Accretion Rates Based on Empirical Relationships
  - Not a mechanistic model
- Overwash component is subject to considerable uncertainty
  - Timing and size of storms is unknown
  - Based on observations of barrier islands after large storms

Mcleod, Poulter, et al., 2010

- *Ocean & Coastal Management* "SLR impact models and environmental conservation, a review of models and their applications"
- SLAMM 5 Advantages
  - Can be applied at wide range of scales
  - Provides detailed information about coastal habitats and shift in response to SLR
  - Can be used to identify potential future land-use conflicts
  - Integrates numerous driving variables
  - "Provides useful, high-resolution, insights regarding how SLR may impact coastal habitats."

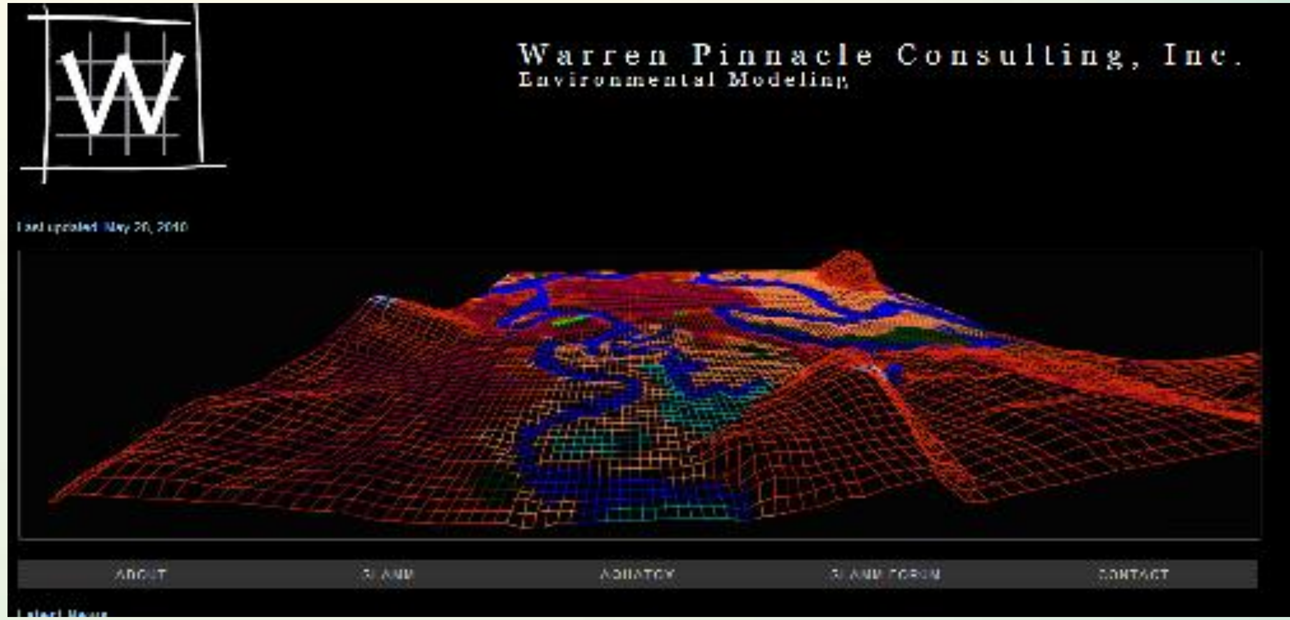
Mcleod, Poulter, et al., 2010

- SLAMM 5 Disadvantages
  - Lacks feedback mechanisms between hydrodynamic and ecological systems
  - Changes in wave regime from erosion not modeled
    - Note wave setup *is* recalculated on basis of land loss
  - Lacks feedback between salinity and accretion rates in fresh marshes
  - SLAMM 6 *does* include feedback between frequency of inundation and accretion rates.
  - Does not include a socioeconomic component to estimate costs; not useful for adaptation policies

Ongoing Work on SLAMM Model

- Ducks Unlimited – Pacific Northwest
  - Application of uncertainty analysis in WA & OR, evaluating land parcels for restoration
- NY State – Application to Long Island, NY City, Hudson River
  - Examine the effects of DEM processing and "hydro enforcement"
- USGS:OR – Linkage created to EPA salinity models/SAV predictions
  - Habitat switching based on salinity, model testing and documentation
- TNC TX – Examine effects on infrastructure given development and restoration scenarios
  - Dike model refined to assess likelihood of overtopping
- USFWS – SLAMM Roads / Infrastructure Module; 64-Bit
- Looking Forward
  - Make "flow-chart" of habitat switching and land-categories modeled completely flexible (international applications)
  - Linkage to hydrodynamic, sediment transport models?
  - More salinity testing
  - Model evaluation and refinement – erosion, overwash, soil saturation
  - Seeking collaborative partners

For More Information



- SLAMM Website (Google "SLAMM")
  - Includes brief model overview, bibliography
  - Updated with latest projects and results
  - SLAMM Forum for Q/A
  - Technical documentation with full model specs
  - Model executable / source code available through the forum
  - SLAMM 6.2 Release (64-bit) Early December 2012
- Email -- jclough@warrenpinnacle.com

warrenpinnacle.com/quals.pdf