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A High-Resolution Area-Time Inundation Index Model (ATIIM) to Assess Habitat Opportunity and Quality under Existing and Alternate Conditions

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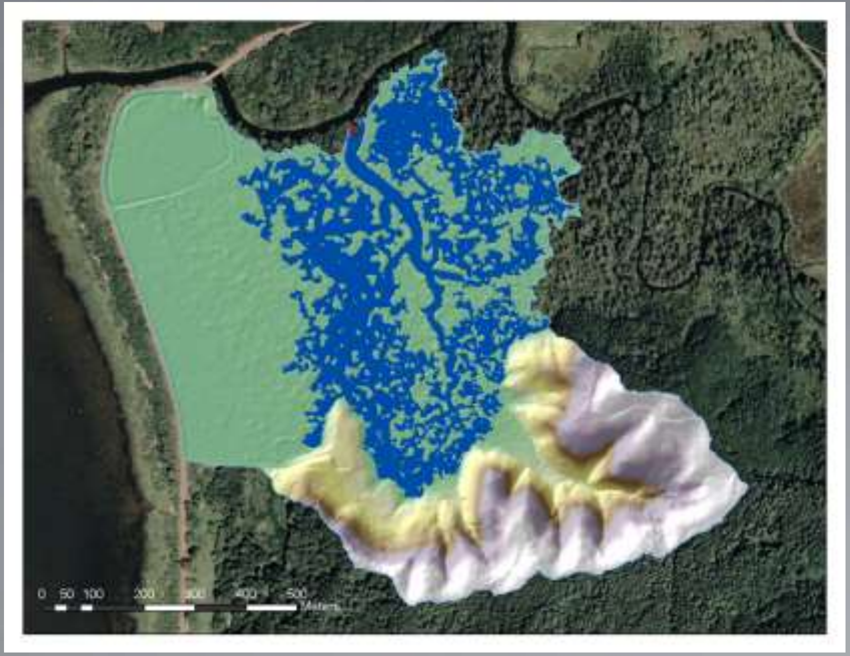


2014 Columbia River Estuary Workshop

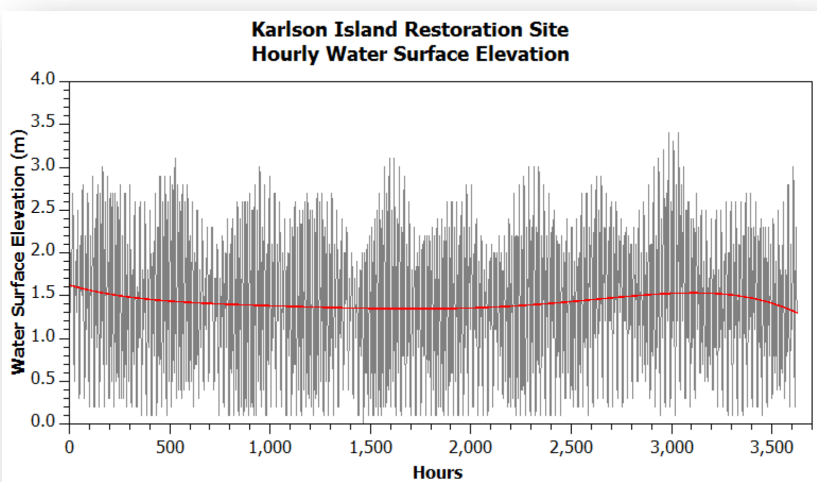
October 22, 2014

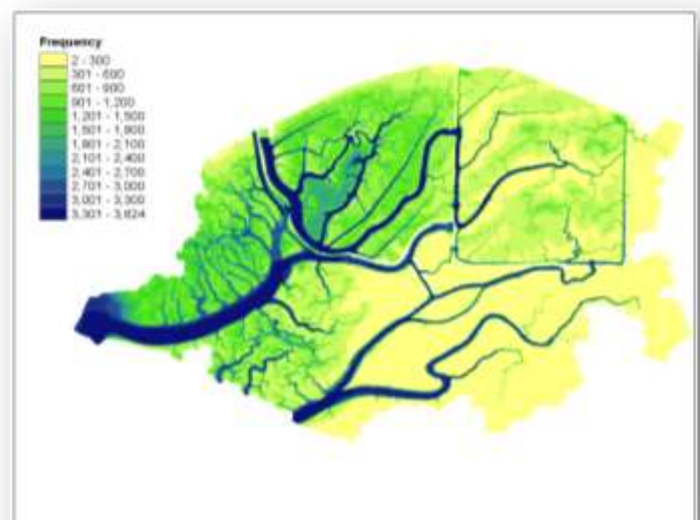
Background and Motivation

- Corps' CRFM Cumulative Effects Study
  - Recognized the need to measure the wetted habitat area directly available to salmon; as well as the wetland area connected to the main stem Columbia River for indirect food web effects.
- Columbia Estuary Ecosystem Restoration Program (CEERP) Research, Monitoring & Evaluation Plan
  - "Habitat availability is associated with the topography and inundation regime, which in turn are associated with geomorphic features such as the total edge and penetration of tidal channels." (Johnson et al., 2008)

Model Design and Philosophy

- Rapid assessment of habitat opportunity and capacity
- High spatial resolution (0.5-1m) for site scale assessment
- Focus on physical system and aquatic and terrestrial habitat opportunity components (structure → function)
- Provide the flexibility to evaluate different time scales and compare different site behavior/conditions
- Adaptable for both tidal and fluvial dominated sites





Model Design and Philosophy

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- Adaptable for different types of channel network morphologies
  - Flow-through, bi-directional, multi-directional, multiple inlet/outlets
- Provide data products and metrics not available elsewhere
- Highly customizable
  - Recently added numerous metrics for calculating avian suitability/disturbance
- Screening-level tool
  - Site restoration and fish and avian habitat potential
  - Restoration design alternatives
    - Use in conjunction with, or as a pre-cursor to more intensive hydrodynamics modeling

Model Application

- Inform hydrologic/physical behavior of existing and/or proposed restoration sites
- Determine trade-offs between inundation level and habitat opportunity and quality
- Compare alternative site restoration designs
  - Dike breach scenarios
  - Terrain modifications
  - Tide gate or culvert modifications

Model Application

- Predict site impacts of altered flow regimes
  - Hydro operations
  - Policy change
  - Climate impacts on flow magnitude/timing/duration
  - Sea level rise
- Aid in determining nutrient and biomass fluxes
  - Flow volume per unit time
- Effectiveness monitoring of changes in the developmental trajectories of restoration sites
  - Adaptive management framework
- Provide standardized site comparisons

Model Overview

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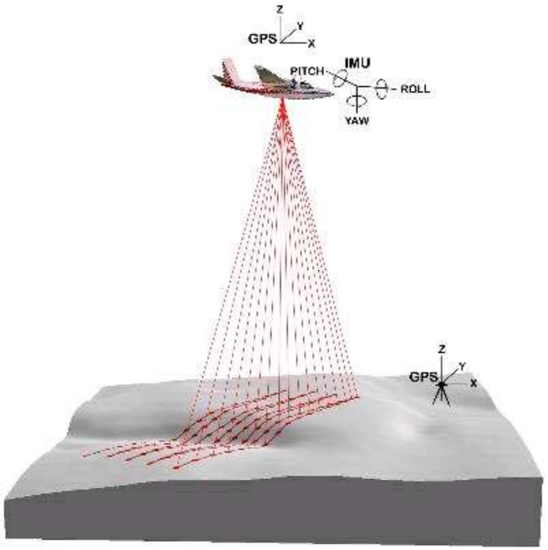
- ATIIM Integrates
  - Advanced terrain processing of high-resolution Light Detection and Ranging (LiDAR) elevation data



  - Available bathymetry data
  - Water surface elevation data
    - In-situ, hydrodynamic or regression-based models, or synthetic
  - An inundated area algorithm that enforces hydrologic connectivity and determines two- and three-dimensional inundation/volume extent over time

Model Overview

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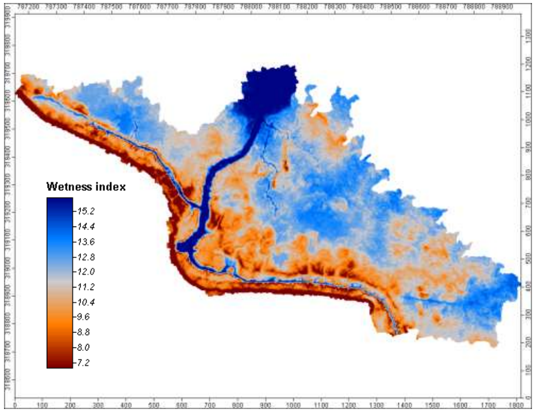
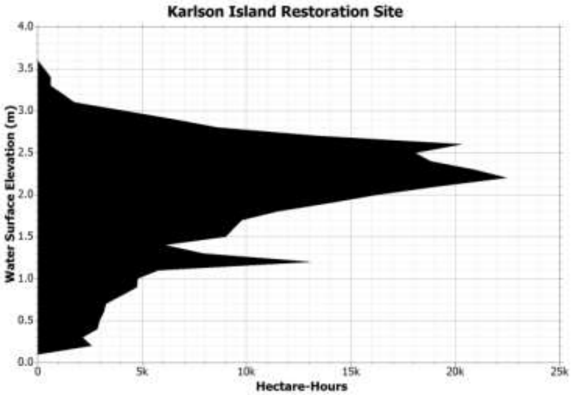
- ATIIM Produces
  - Three general classes of data output



Spatial

	CC	KI	SS	SR
Time-Steps (hr)	3625	3624	3625	3593
Total Area (ha)	77.6	15	7.9	50
Bankfull Elevation (m, NAVD88)	2.7	2.6	2.5	2.5
% Time of Overbank Inundation	18.7	6.8	14.8	17.4
Total Hectare-Hours	9629	913	1230	7269
Hectare-Hours ≥ Bankfull	8064	607	745	5345
	-83.80%	-66.50%	-60.50%	-73.50%
Hectare Hours < Bankfull	1565	306	486	1924
	-16.30%	-33.50%	-39.50%	-26.50%
Max. Possible Hectare Hour Inundation	140680	27232	14219	89247
Area-Time Index	5.7	2.2	5.2	5.9

Tabular

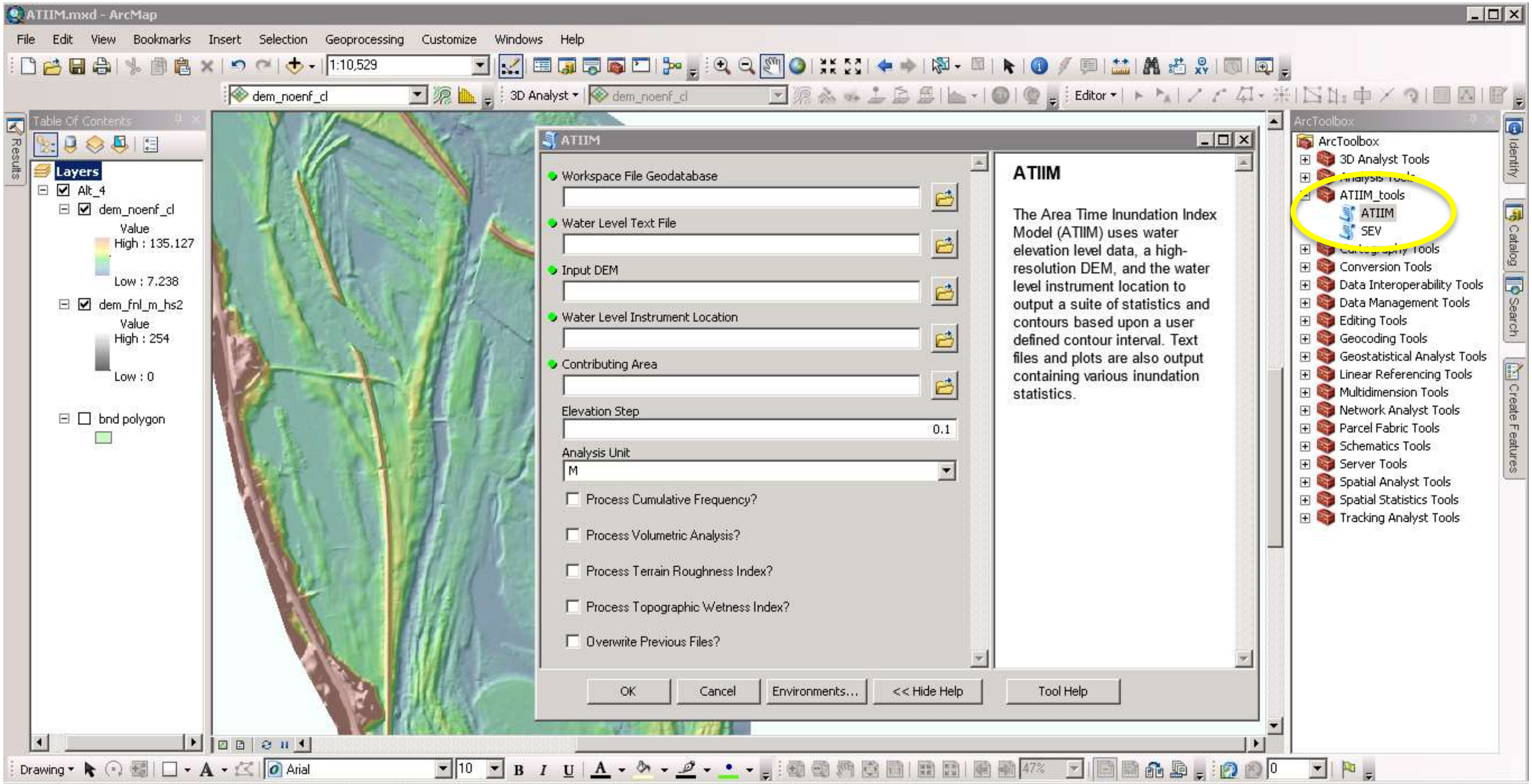


Plots

  - *14 spatial metrics (some varying over time and space)*
  - *49 tabular metrics* useful for predicting hydrological and biological outcomes

Model Development

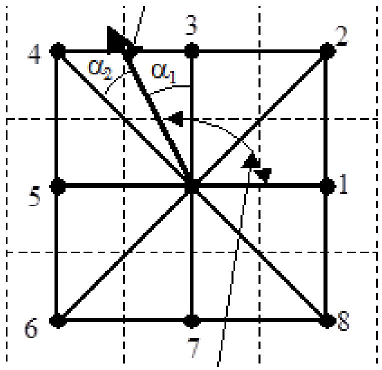
- Migration of model to a toolbox module within ArcGIS
  - Objective: Push the toolbox and documentation to public domain



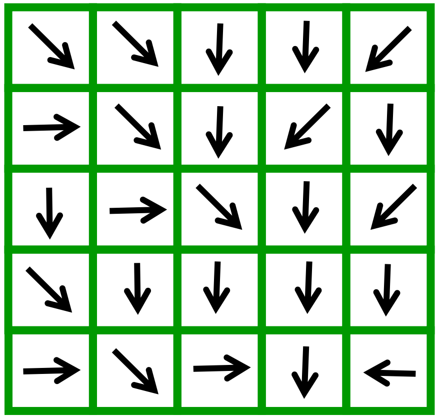
- Terrain Processing
  - Finite-difference, multi-grid, locally adaptive terrain analysis method after Hutchinson (1988, 1989, 1996, 2009)
  - Can use multiple sources of data
    - non-regularly gridded elevation data, contours, xsect
  - Factors in uncertainty in the source data
  - Incorporates profile curvature, planimetric curvature, and total curvature as terrain roughness penalties
    - Provides for a realistic terrain surface honoring principles of morphometry and hydrologic flow
    - Highly effective for processing complex, high-density, low-relief terrain → reveals microtopography

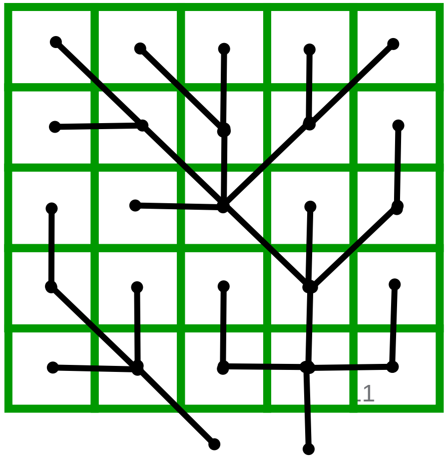
Terrain Analysis

- Deterministic Infinity Method (D∞) (Tarboton 1997)
  - Produces flow direction, flow accumulation, flow paths, and upslope contributing area
  - Elevations of surrounding 8-cells determined
  - Cells split into planar triangular facets
  - Direction of steepest descent determined
  - Very effective for use in low-relief areas



- Deterministic-8 Method
  - Most common method
  - Not sensitive enough





Inundated Area Algorithm

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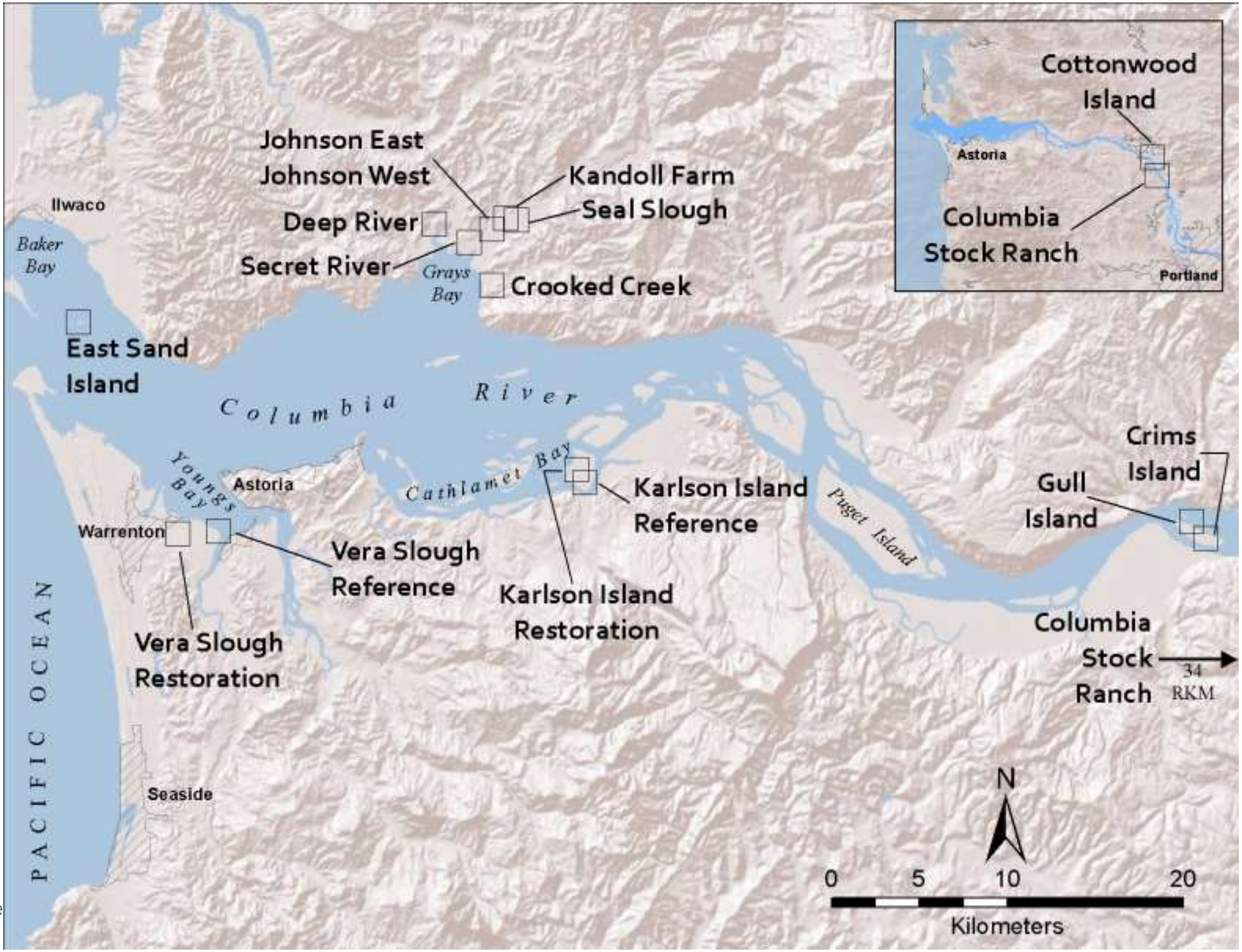
- Inundation Slices
  - Region growing algorithm
    - Remote-sensing/image processing based method for classification/image segmentation
    - Uses kernel/seed point (WSE sensor) to grow from
    - Criterion:
      - Must always proceed in direction of flow
      - Cannot proceed past defined catchment boundary
      - Must honor matrix Z values and not exceed current process-step WSE value
    - To grow from kernel, evaluation of adjacent model cells takes place, those that meet the criterion are added to the cluster
    - Method enforces hydrologic connectivity from the kernel
    - Area and volume of the inundation slice is calculated and stored

Model Sites


Cottonwood Island
Astoria
Columbia Stock Ranch
Portland
Johnson East
Johnson West
Kandoll Farm
Seal Slough
Ilwaco
Deep River
Baker Bay
Secret River
Grays Bay
Crooked Creek
East Sand Island
Columbia River
Youngs Bay
Astoria
Cathlamet Bay
Karlson Island Reference
Puget Island
Crims Island
Gull Island
Warrenton
Vera Slough Reference
Karlson Island Restoration
Vera Slough Restoration
Columbia Stock Ranch
34 RKM
PACIFIC OCEAN
Seaside
N
0 5 10 20
Kilometers

Inundated Area

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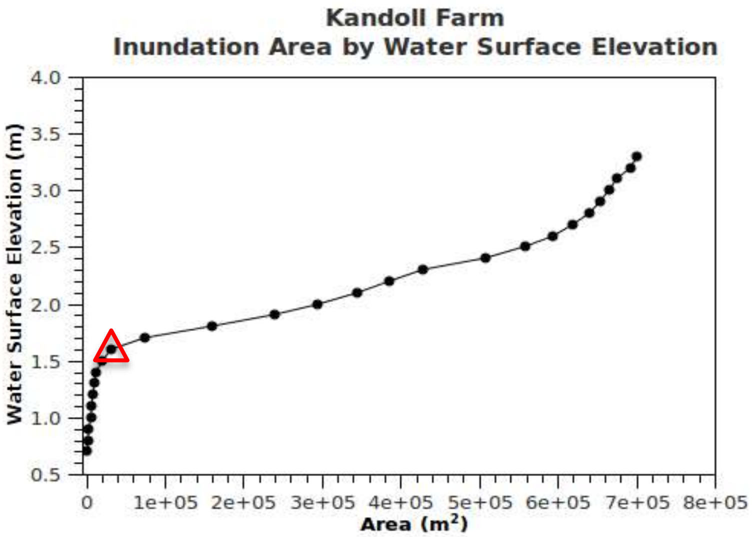
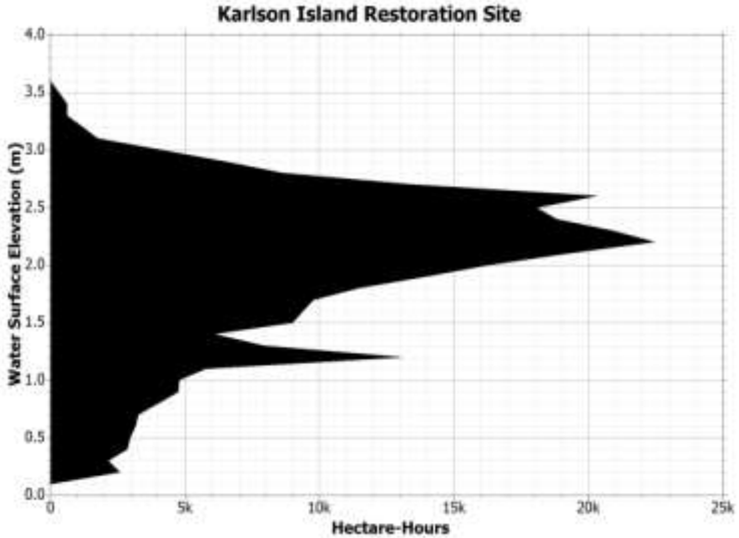
Inundated Area

Example Outputs

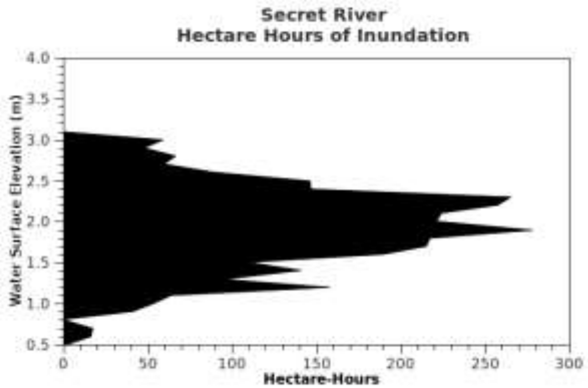
- **Elevation/Area Relationship**
- **Bankfull Elevation**
- **Percent Time of Overbank Inundation**
- **Total Hectare Hours:** The total number of hectares inundated at each time and elevation-step through the study period.

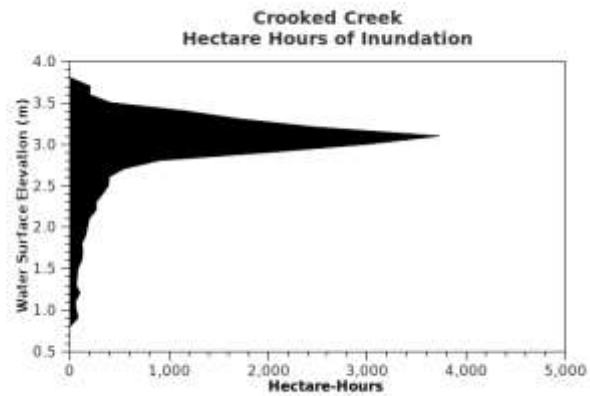


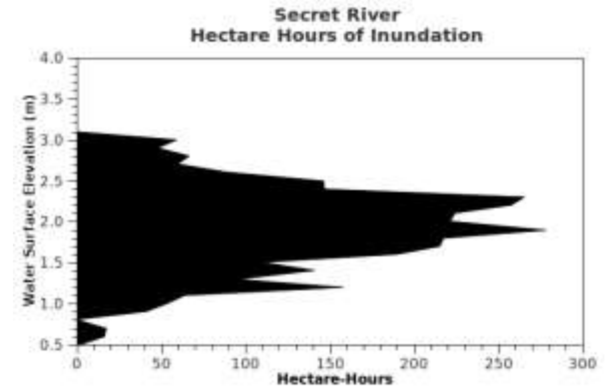


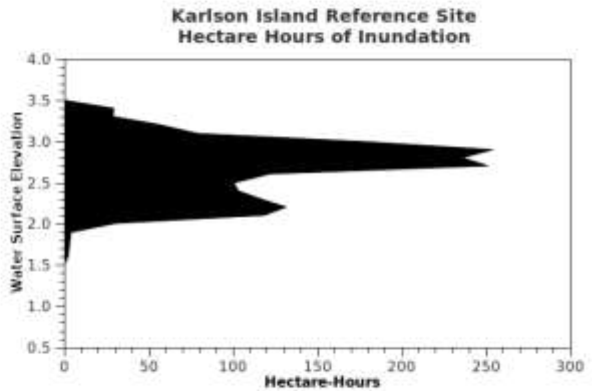
Example Outputs

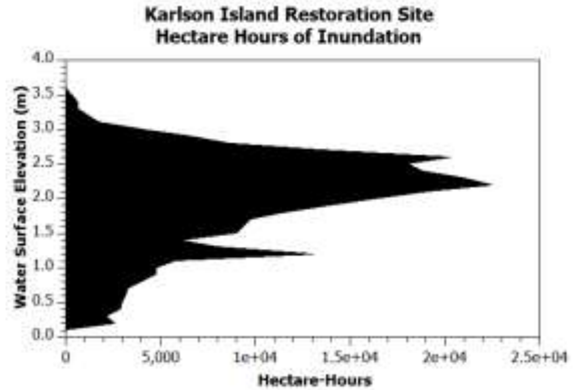
- Hectare-Hours of Inundation

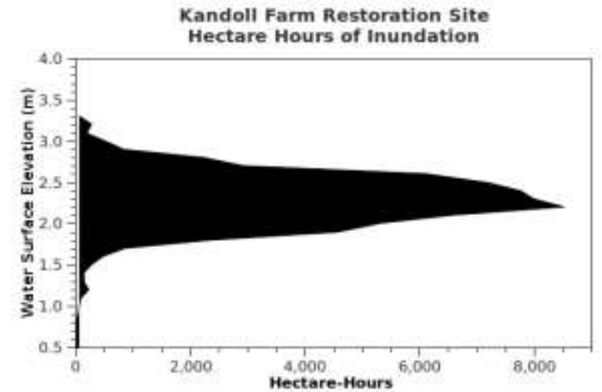






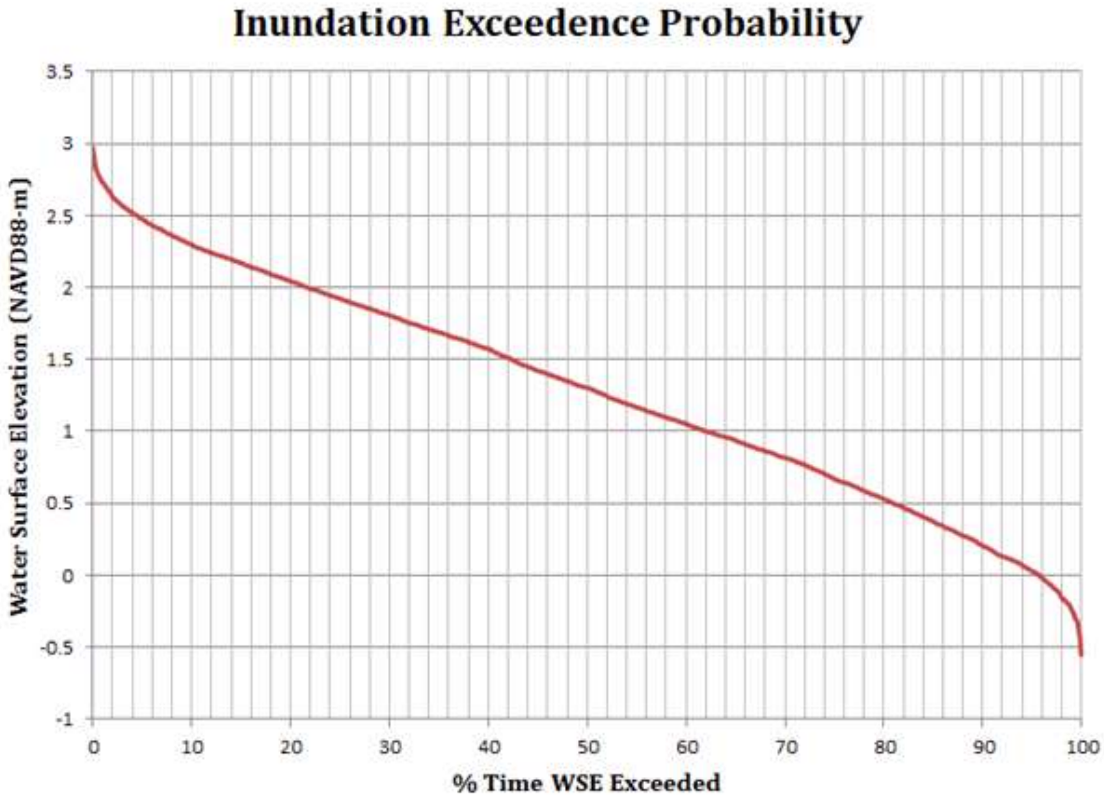






Example Graph Outputs

- **Inundation Exceedence Probability**:
  A measure to indicate the probability of occurrence (based on the historical record) for a specific elevation to be inundated. A value of 99% would indicate that the particular elevation is inundated often (lower elevations) and a value of 1% would indicate rare occurrences of inundation (high elevations).



Sum Exceedence Value (SEV)

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- ATIIM-SEV analysis to estimate major plant communities (Borde et. al)
  - SEV metric is based on patterns of inundation during vegetation growing season
  - Project the future potential vegetation distribution under altered climate / sea-level rise scenarios

Alternative Design Scenarios

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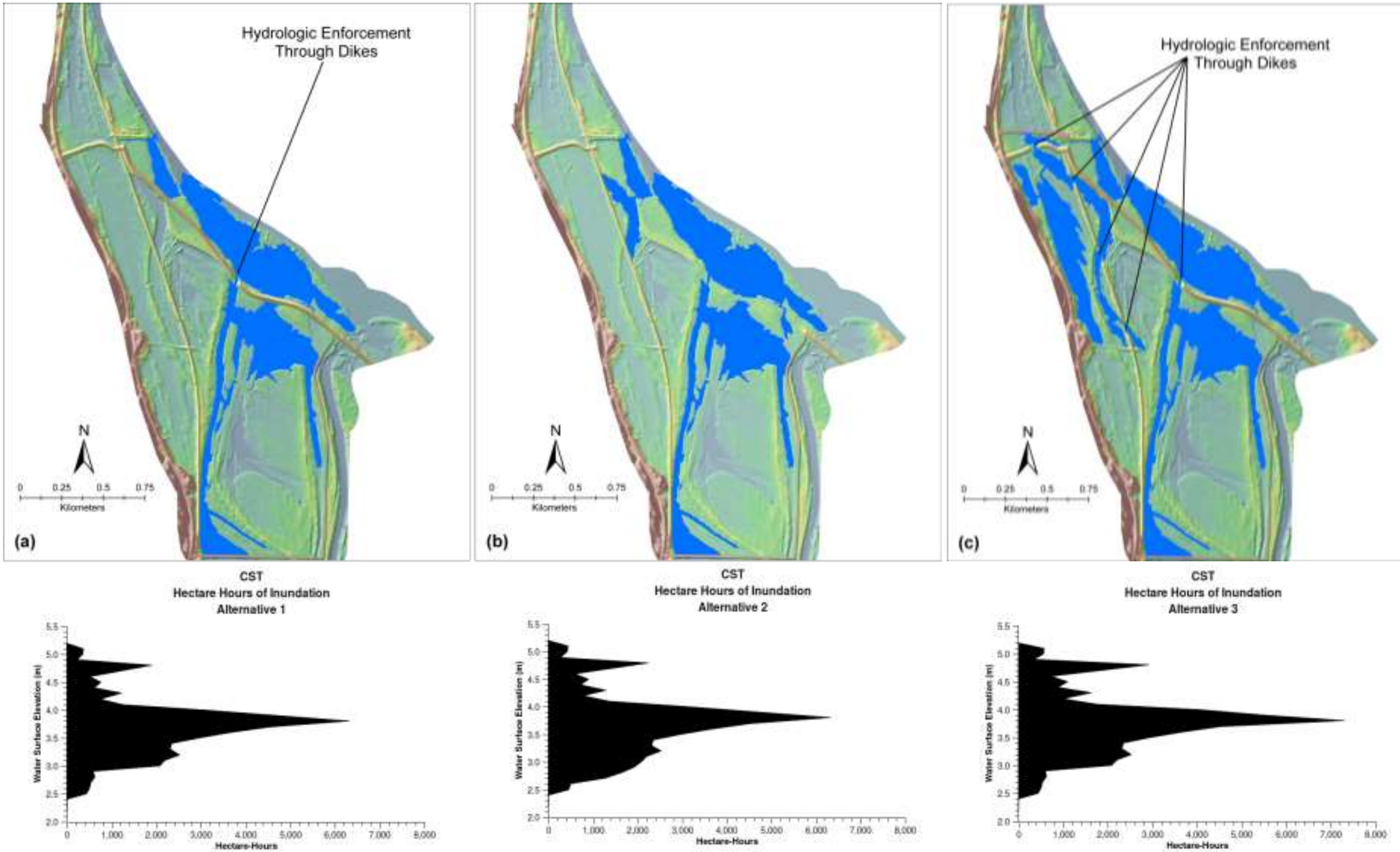
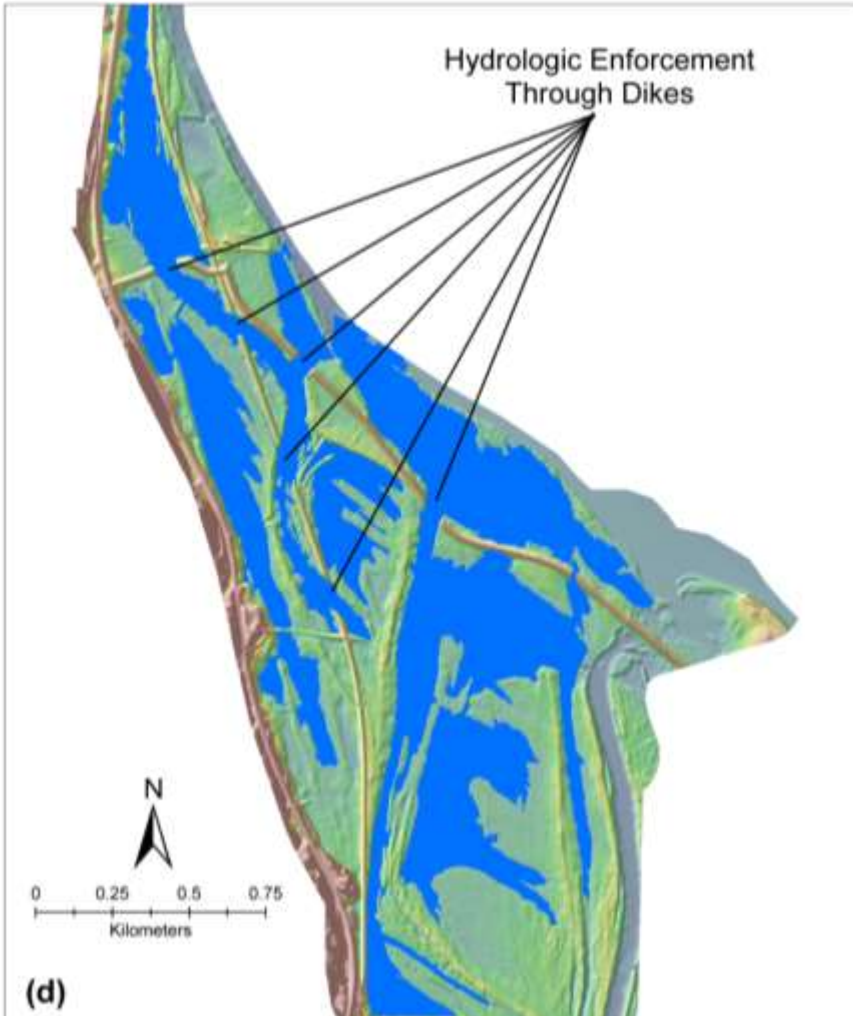
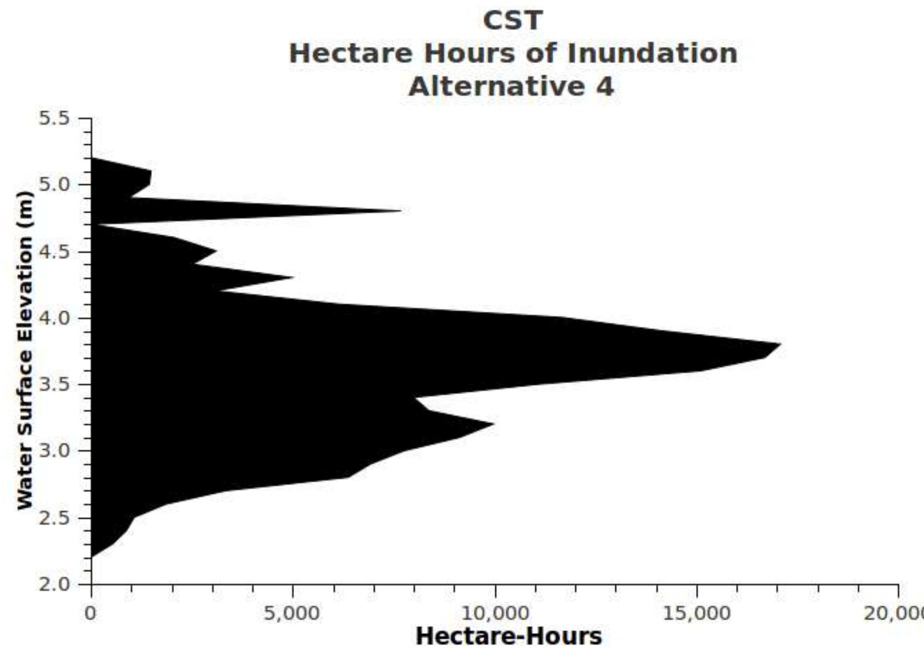
- Columbia Stock Ranch (WSE = 4.1m)



Alternative Design Scenarios

- Columbia Stock Ranch (WSE = 4.1m)





- Minimal differences between alternatives 1-3
- Alt 4 came later as a result of Alts 1-3 findings and met restoration planning objectives

Current / Future Work

- Efforts underway to migrate current model into ArcGIS framework
  - Provides a user-friendly and familiar interface
  - Couple with other existing capabilities within ArcGIS
  - Ability to link data to network geodatabases and/or web-based data services
  - Requires linking specialized terrain-processing and hydrologic extraction codes into ArcGIS
  - Incorporating programmable plotting packages that can read from a geodatabase

- Incorporate simplified 2D fluid dynamics to represent bed gradients, bed roughness, WSE slope, etc., to get at cell-based flow, constriction/ponding effects, lag times, mixing, etc.

Peer-Reviewed Publications

Diefenderfer, HL, AM Coleman, AB Borde, IA Sinks. 2008. Hydraulic geometry and microtopography of tidal freshwater forested wetlands and implications for restoration, Columbia River, U.S.A., *Ecohydrology and Hydrobiology,* 8(2-4), pp. 339-361.

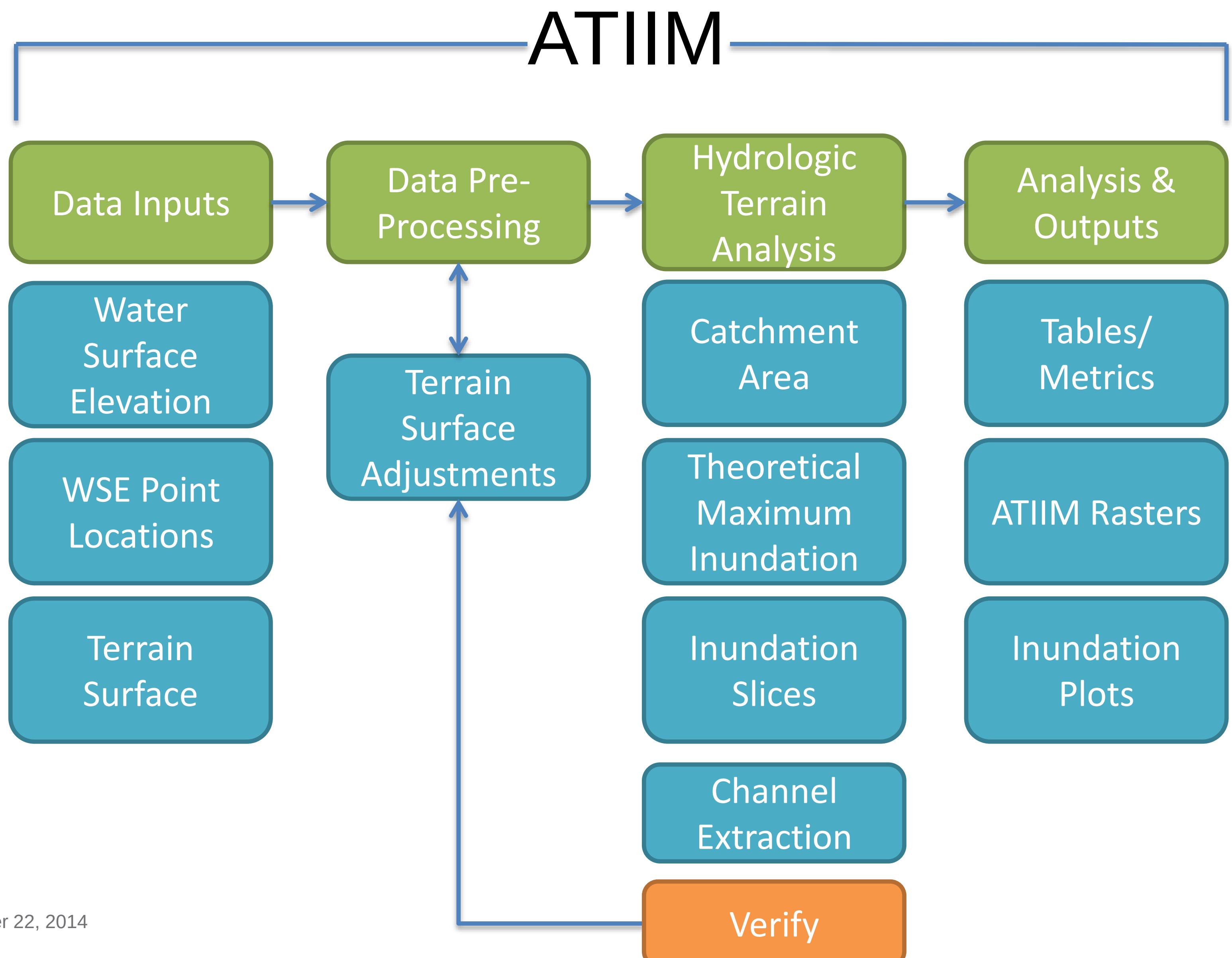
Coleman, AM, HL Diefenderfer, DL Ward, AB Borde. Spatially Based Area-Time Inundation Index Model Developed to Assess Habitat Opportunity in Tidal Wetlands and Restoration Sites, *Ecological Engineering, in review*.

Acknowledgements

- **U.S. Army Corps of Engineers – Portland District**
  - Blaine Ebberts
  - Cindy Studebaker
- **Columbia Land Trust**
  - Scott McEwen
  - Ian Sinks
- **NOAA – Northwest Fisheries Science Center**
  - Curtis Roegner
- **PNNL**
  - Gary Johnson
  - Ron Thom
  - Shon Zimmerman
  - Ron Kauffman

Backup Slides

Model Workflow



Tidal Exchange Volume Metrics

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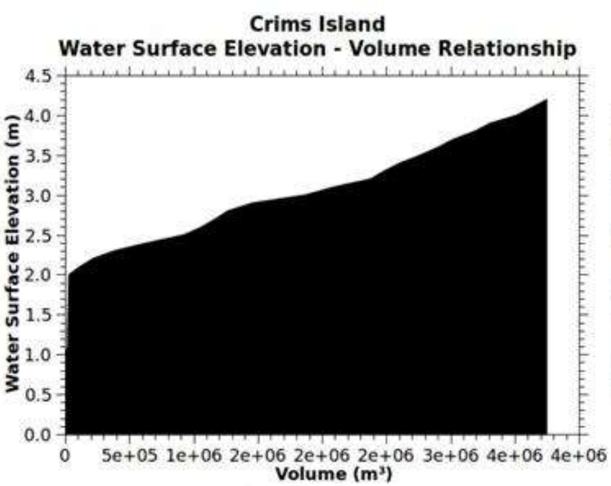
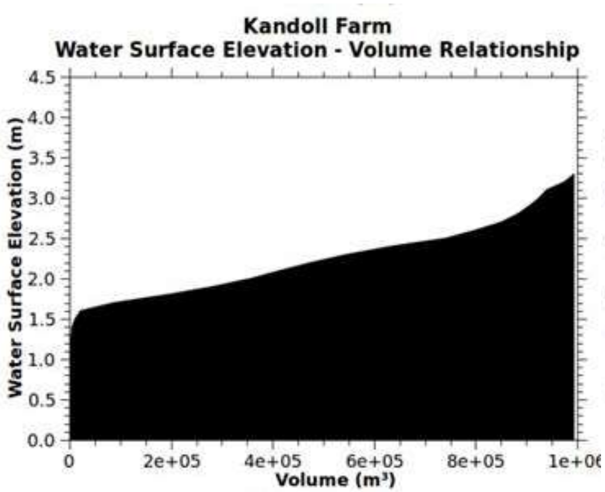
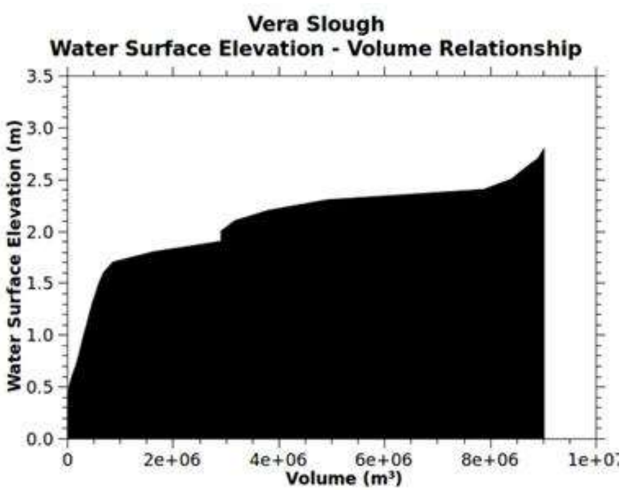
- **Time Volume Inundation Index:** The percent time of volumetric inundation is calculated as the actual volume of water, including both in-channel and floodplain area, summed at 10-cm increments of elevation, and divided by the theoretical maximum acre-feet-hours for the site.

- **Surface-Area to Volume Ratio:** Ratio of the planimetric surface area to the three-dimensional volume at each 10-cm increment of elevation.







Additional Inundation Metrics

- **Maximum Water Surface Elevation Frequency (MFWSE):** Most frequently observed water surface elevation in the period of record.
- **Habitat Opportunity at MFWSE:** The habitat opportunity percentage and length at the most frequently observed water surface elevation in the period of record.
- **Inundation Perimeter:** Data series of the total perimeter length of inundated area at each 10-cm increment in the WSE data record. This measure of the aquatic-terrestrial interface provides information about site characteristics and the potential for habitat opportunity and nutrient/biomass flux.
- **Inundation Perimeter at MFWSE:** The inundation perimeter length at the most frequently observed water surface elevation in the period of record.
- **Water Surface Elevation Percent Frequency at Bankfull Elevation:** WSE frequencies greater than or equal the mean bankfull elevation provides an indicator of the potential frequency that fish could access the marsh edge for feeding.
- **Total Site Channel Density:** Stream channel length per unit area calculated by dividing the total center-of-channel length at the site by the total site area.
- **Inundated Channel Density:** Stream channel length per unit area calculated at each 10-cm increment of elevation providing a measure of density in the aquatic/terrestrial interface over varying tidal/flow levels.

Example Aquatic Habitat Metrics

- **Drainage density**: Stream length per unit area (total channel length/catchment area) (Horton 1932)
- **Drainage density at each inundation level**: Measure of density in the aquatic/terrestrial interface over varying tidal/flow levels
- **Total channel edge length**: Captures the total potential habitat opportunity on either side of the channel
- **Total channel edge length at each inundation level**: Measure of total potential habitat opportunity with varying tidal/flow levels
- **Habitat Opportunity Metric**: Determines the percent of total access opportunity, by summing the length of inundated channels at a given WSE and dividing by the sum of channel length for the entire site

Terrestrial Habitat Availability Metrics

- **Cumulative Frequency of Inundation**: This metric describes how often, on the basis of percent of total possible time, a specific elevation has been inundated over the study period.

- **Total Non-Inundated Hectare-Hours**: The sum of the total number of hectares at a site that are not inundated (i.e., dry areas) at each hourly time-step over the study period.
  - User-defined study period – 24 hours/day
  - Dry hectare hours at night per week

- **Longest Duration of Non-Inundation**: The longest period of time, in hours, that a specific elevation did not get inundated with a minimum 0.2 m water depth.
  - Evaluate at user-defined time-periods, i.e., weekly, monthly

Terrestrial Habitat Availability Metrics

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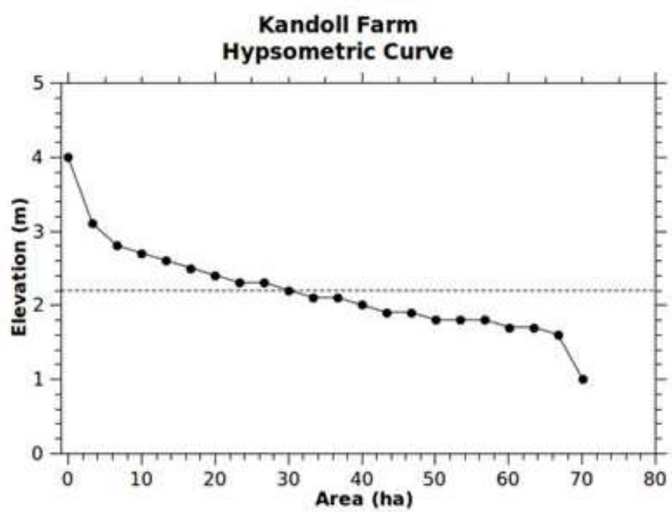
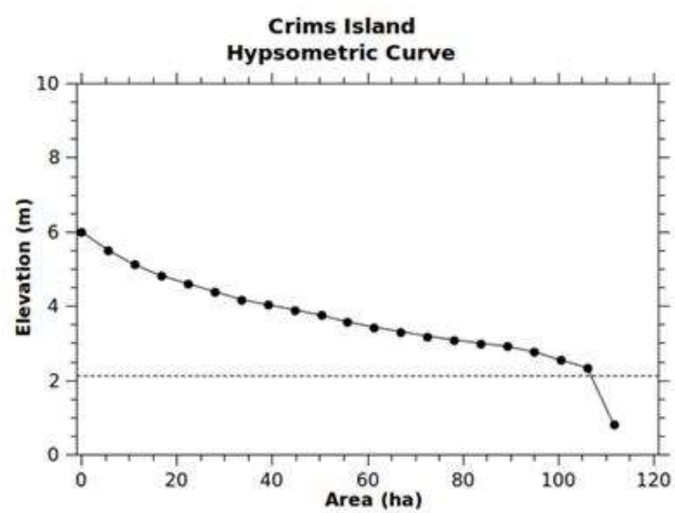
- **Mean Site Inundation Depth**: The average water depth for the site at a given water surface elevation.
- **Functional Hectares Excluded**: This is a general metric to understand how water inundation would affect nesting/foraging locations.
- **Sum Exceedence Value**: Cumulative sum of the difference between hourly water surface elevation and land surface elevation during the growing season. Used as an indicator for vegetation communities.

- Site Hypsometry
  - Hypsometric curve (Harlin 1978)
    - Cumulative probability distribution that captures the elevation-area relationship of an area.
  - Captures general topographic landform
  - Quick assessment of site
    - Opportunity for inundation and habitat opportunity





ATIIM Raster Outputs

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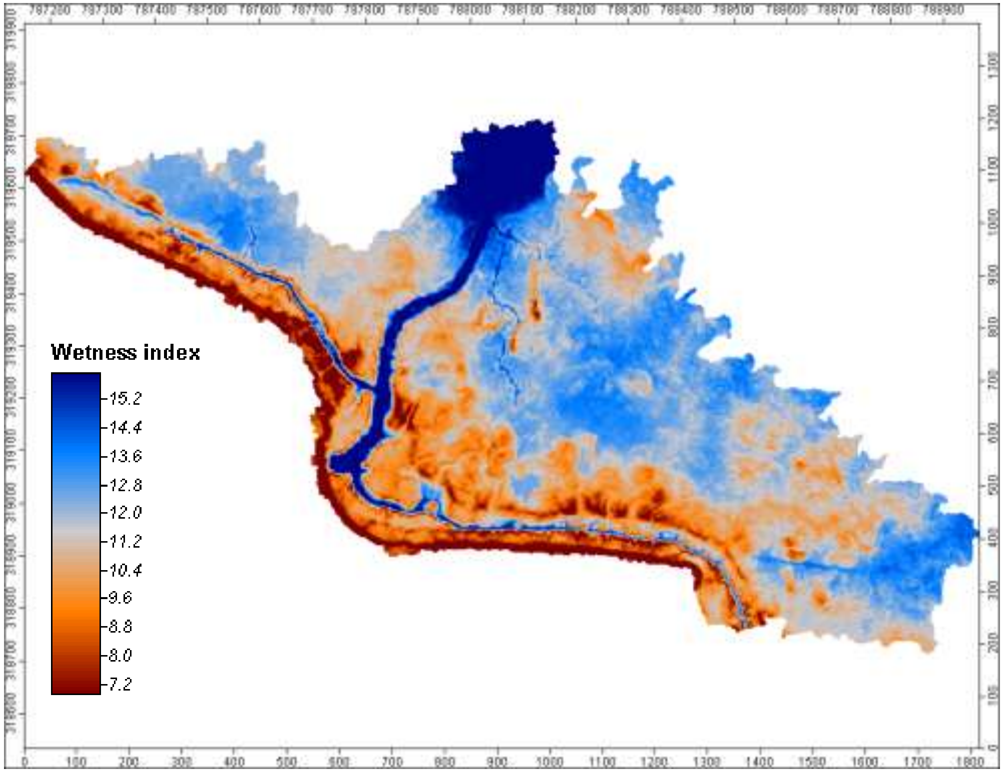
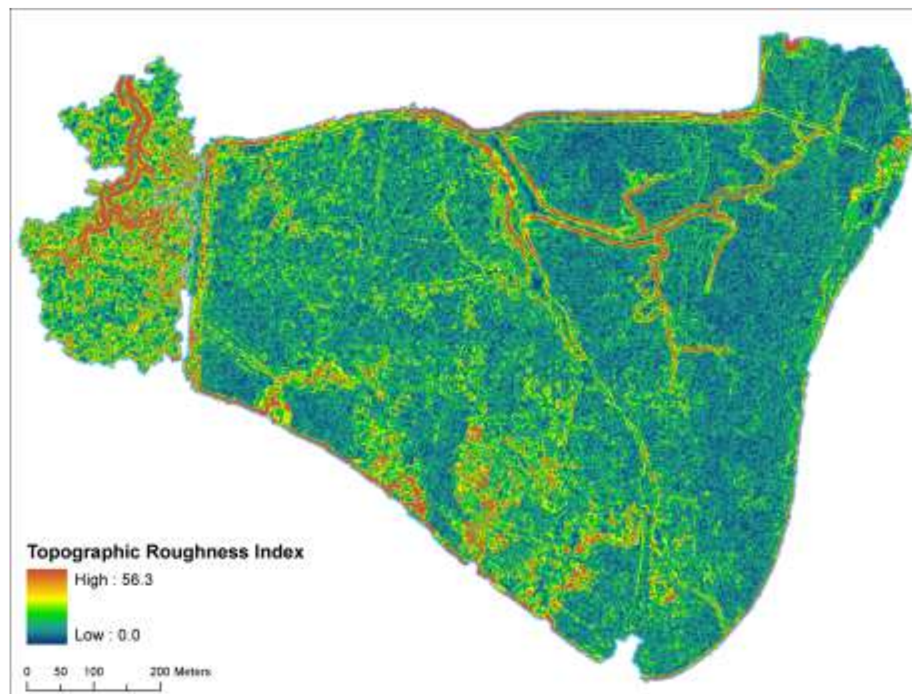
- Modified Topographic Wetness Index (Boehner et al. 2002)
- The modified topographic wetness index (MTWI) estimates a spatially distributed steady-state condition of soil saturation and, ultimately, runoff generation.
- The MTWI can provide value in determining existing and potential restoration wetlands based on natural topography.
  - Combined MTWI with newly developed rule-based object-oriented classification methods of remote-sensing data has been applied in non-estuarine wetland mapping programs with a high-degree of success (Coleman 2010).



ATIIM Raster Outputs

- Topographic Roughness Index (Riley et al. 1999)
- Evaluates elevation differential between kernel cell and surrounding neighbors
- Reference sites tend to have a higher surface roughness over restoration sites (Diefenderfer et al. 2008).
- The topographic roughness index can be used as a metric for restoration progress and habitat opportunity; e.g., at Sitka spruce swamp sites characterized by hummocky microtopgraphy.



ATIIM Raster Outputs

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- Cumulative Frequency of Inundation
  - Cell by cell cumulative frequency over time series