The FESD Delta Dynamics Modeling Collaboratory
A Progress Report

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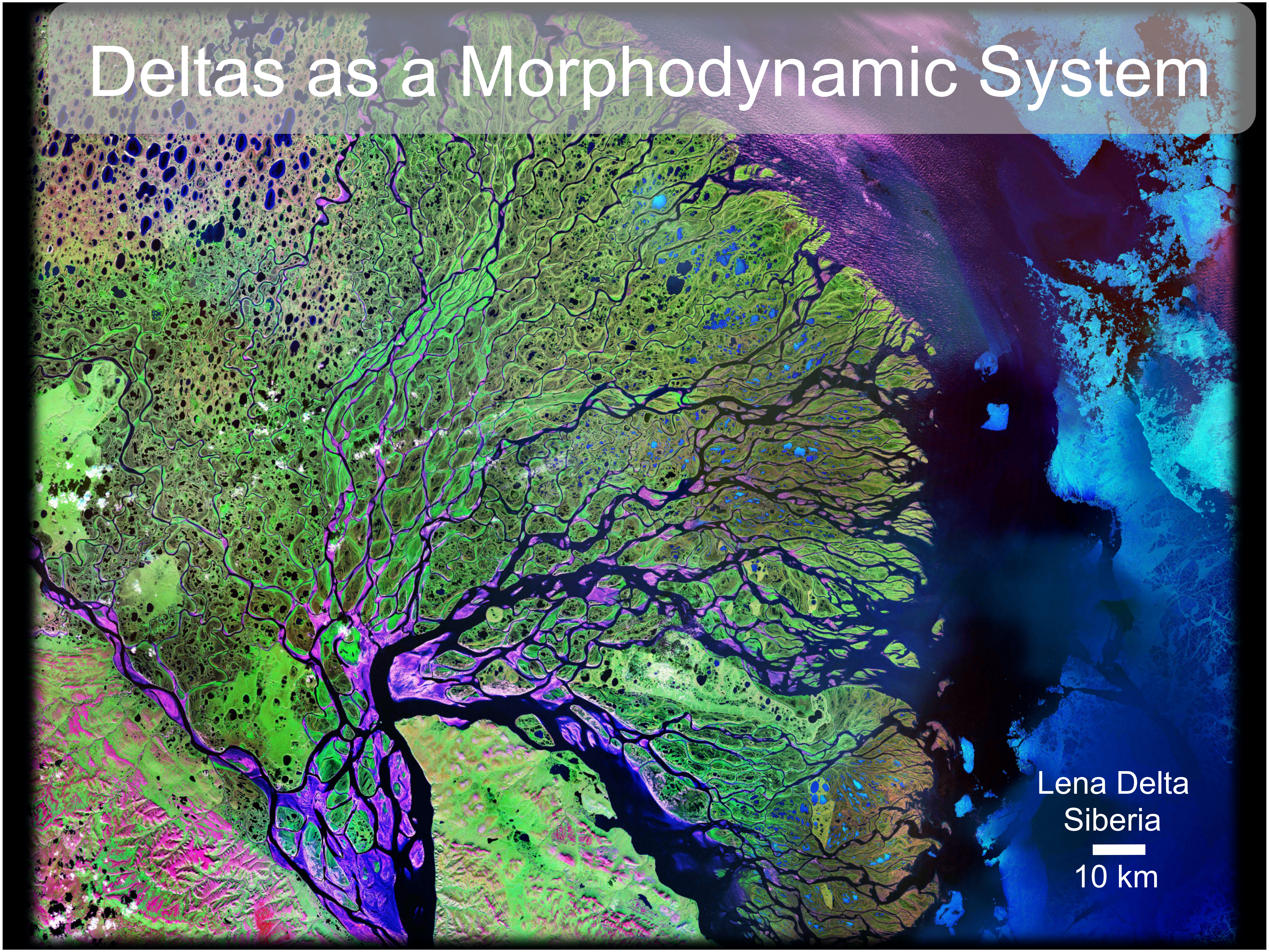
Funded by the National Science Foundation FESD and CSDMS Programs

Deltas as a Morphodynamic System

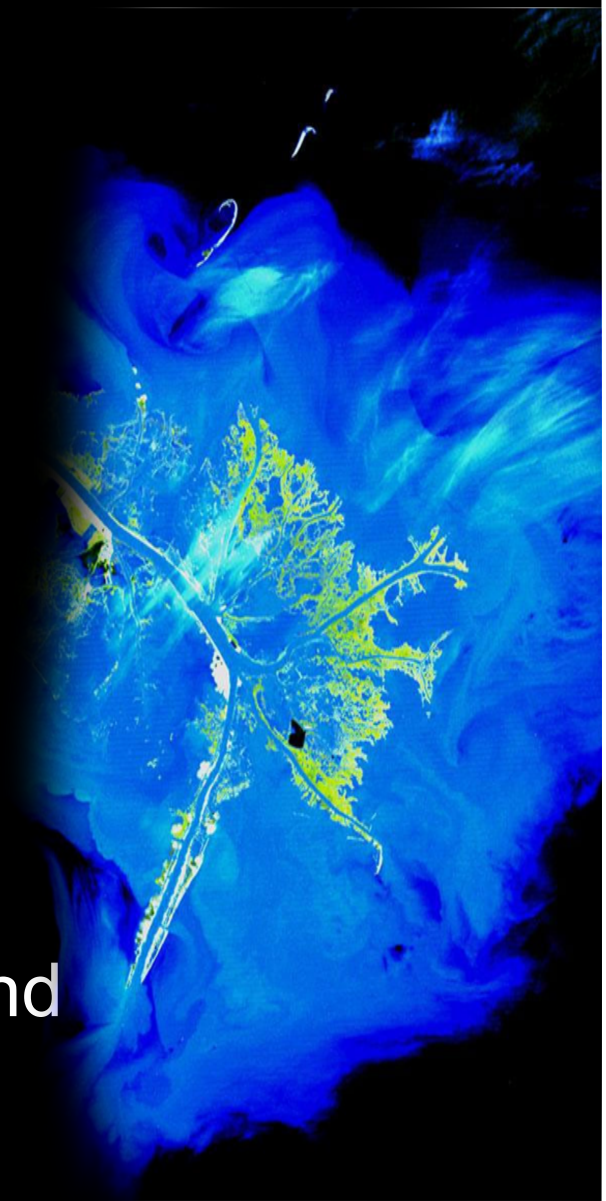


Deltas as a Morphodynamic System

Gilgel Abay River Delta in Tana Lake
Ethiopia

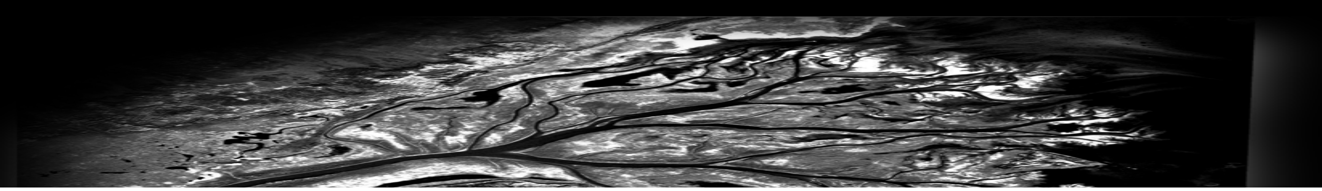
Questions

- How do deltas self-organize into such diverse natural geomorphic forms?
- What are their feedback loops and parameters governing the length scales and response times?
- How will deltas respond to perturbations in sediment fluxes and types, sea level rise, changes in salt/nutrient fluxes, and climate change?



FESD Delta Dynamics Collaboratory (DDC)

- Five-year effort to develop tested, high-resolution, quantitative models incorporating morphodynamics, ecology, and stratigraphy to predict river delta dynamics over engineering to geologic time-scales
- Funded through the National Science Foundation's "Frontiers in Earth System Dynamics" (FESD) Program
- Specifically address questions of delta system dynamics, resilience, and sustainability



FESD Delta Dynamics Collaboratory

- Two laboratories
  - Wax Lake Delta—a field laboratory for discovering process-interactions and testing model predictions (contact Dave Mohrig--mohrig@jsg.utexas.edu--for more information)
  - Virtual Modeling Laboratory in CSDMS for model development and hypothesis testing
    - Three types of models
      - reduced complexity
      - multidimensional ecomorphodynamic
      - ecologic

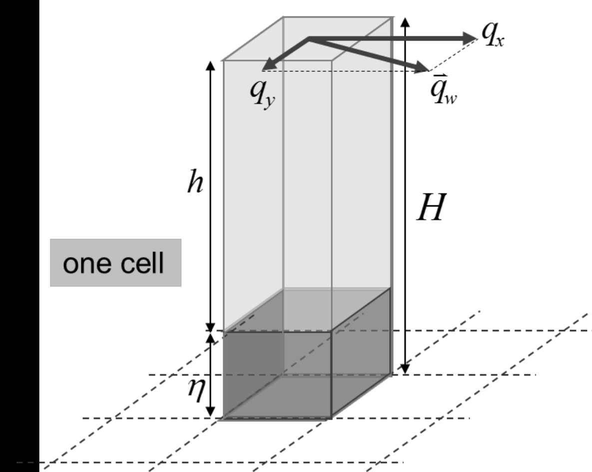
Reduced Complexity Delta Models (RCDM)

- *DeltaRCM* a “2.5-D” cellular delta formation model
  - Team: Man Liang, Paola Passalacqua, Corey Van Dyk w/ collaborators Doug Edmonds, Nathanael Geleynse, Vaughan Voller, Chris Paola
  - Focus on large-scale system dynamics

DeltaRCM

Cellular routing framework

- Lattice domain of square cells
- Calculates unit discharge vector, bed elevation and water surface elevation at each cell



Weighted random walk

- Water and sediment flux are treated as "parcels" in a Lagrangian view
- Parcels are routed stochastically based on a probability field calculated from simplified physics

At each time step

- Calculate routing probabilities for water parcels
- Route water and update flow field and water surface elevation
- Calculate routing probabilities for sediment parcels
- Route sediment and update bed elevation

DeltaRCM

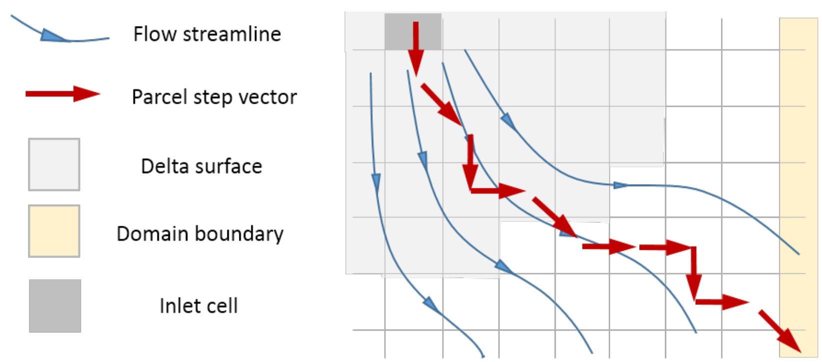
Water Routing Probabilities

Key elements in deciding the routing weight (probability) of flow to a neighbor cell

- Water depth in that cell (an approximation of conductivity, or the inverse of flow resistance)
- Whether the cell is in the "downstream" direction (determined by a combination of flow inertia and water surface gradient)

$$w_i = \frac{h_i max(0, \overline{F}\ \overline{d}_i)}{\Delta_i}$$

Water surface is updated along the paths of water parcels assuming a 1-D profile (finite difference scheme)

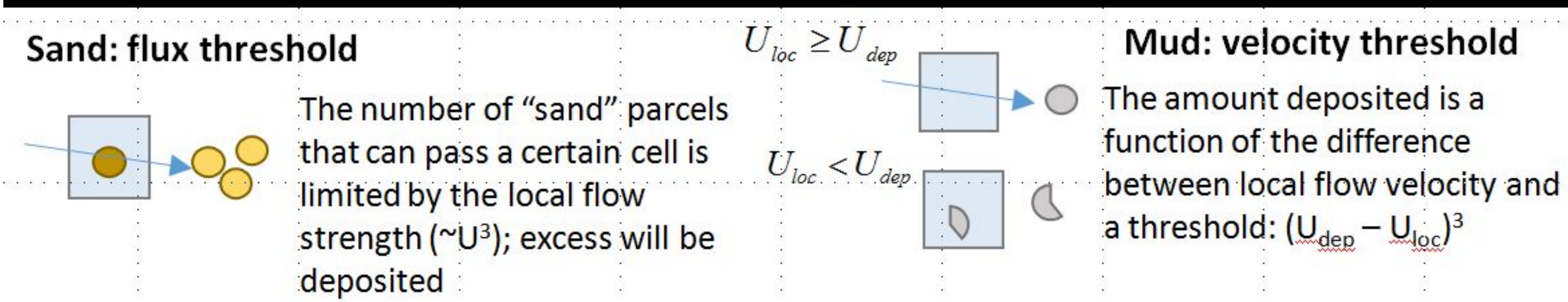


DeltaRCM

Sediment Routing Probabilities

Two types of sediment parcels (sand/mud) that have:

- Different routing probabilities
- Different rules for deposition/erosion



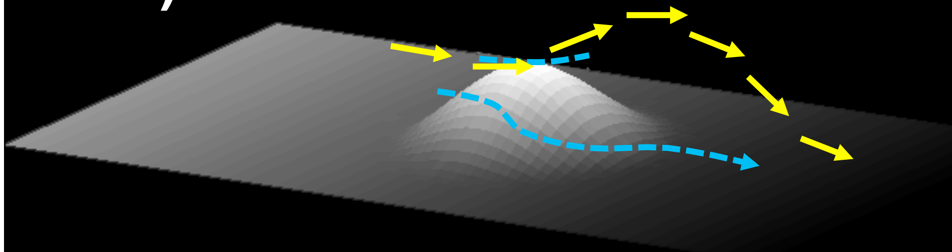
Updating topography

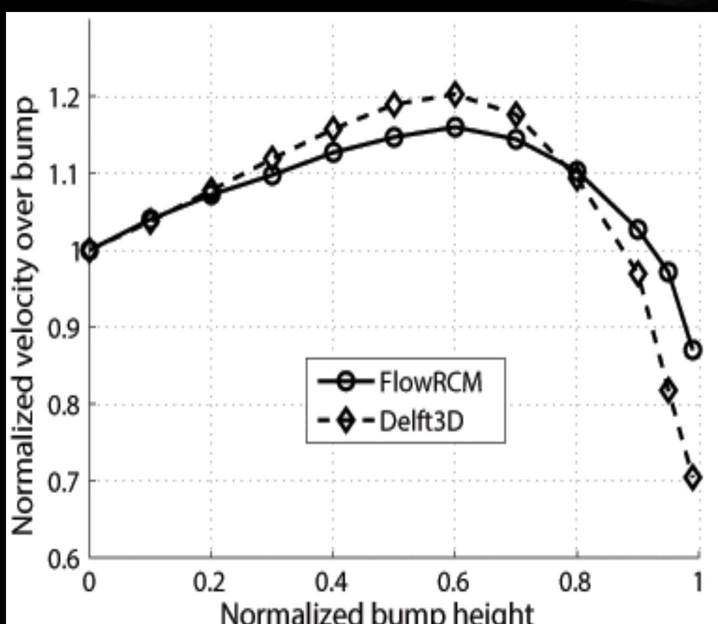
- A sediment parcel loses mass by deposition and gains mass by erosion; the bed adjusts accordingly
- Erosion and deposition are determined by local flow conditions

DeltaRCM

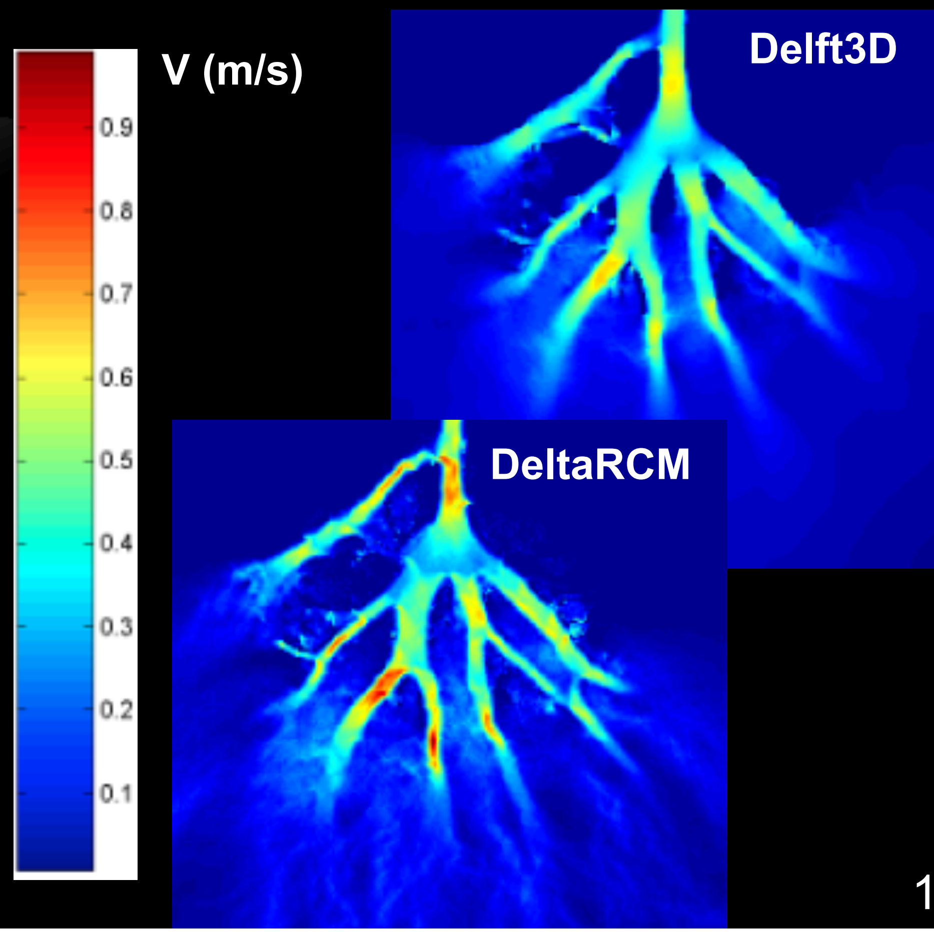
Validation of the hydrodynamic component

Flow over a bump (river mouth bar)





Flow through Wax Lake network



Other Reduced Complexity Models

- A network-based modeling framework for understanding delta vulnerability to change
  - Team: Efi Foufoula-Georgiou, Alej Tejedor, Anthony Longjas, Ilya Zaliapin
  - Map delta network into a directed graph composed of a set of nodes (or vertices) and links (or edges) and represented by its connectivity or adjacency matrix
  - Operations on the adjacency matrix quantify immediate or distant connectivity, distinct sub-networks, and downstream regions of influence from any point on the network.
  - Use these representations to construct “vulnerability maps”

Other Reduced Complexity Models

- A network-based modeling framework for understanding delta vulnerability to change

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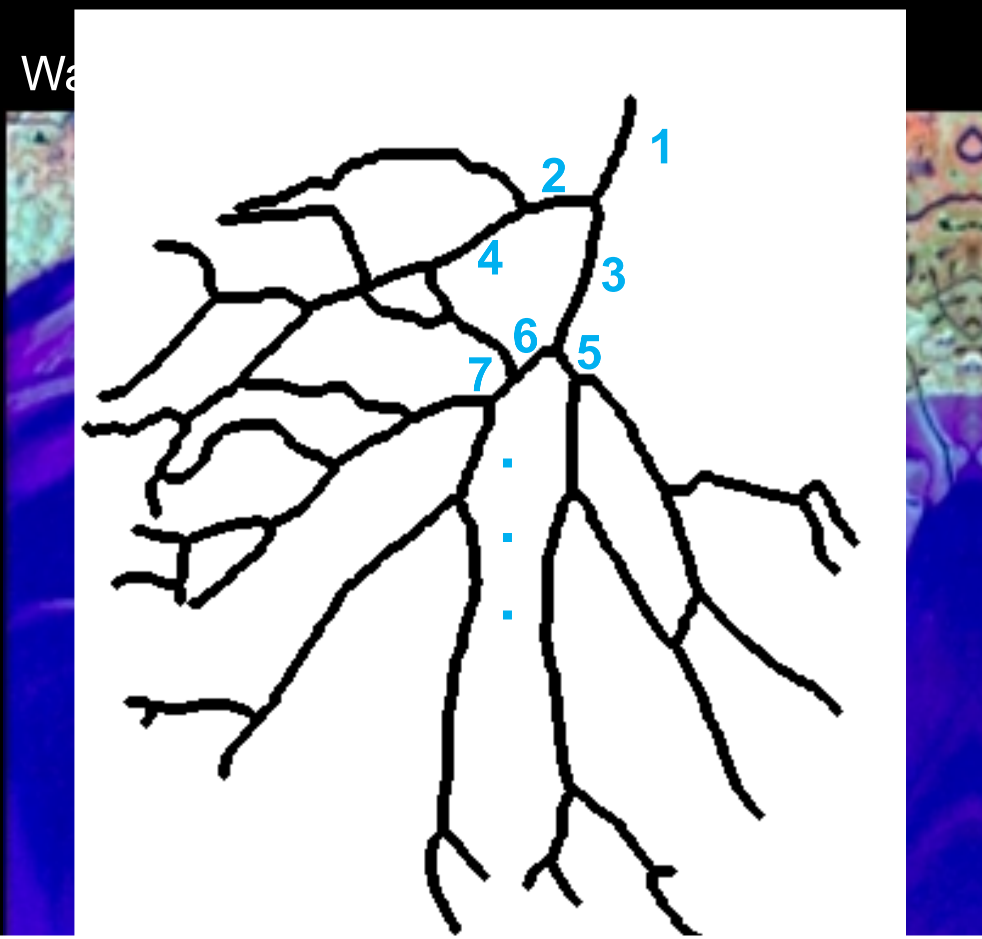


- **Directed Graph**:
  - Node → Junction
  - Link → Stream
- Index each link
- *N* is the total number of links = 59

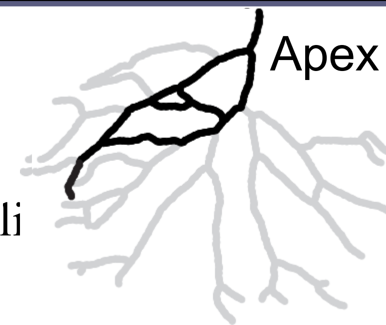
Adjacency Matrix *A* (*N* x *N*)

$$\begin{cases} A_{ij} = 1^* & \text{if there is a connection } i \rightarrow j \\ A_{ij} = 0 & \text{otherwise} \end{cases}$$

(Note: 1* replaced with w_{ij} for flux propagation)

Other Reduced Complexity Models

1. **<u>Find Sub-networks</u>** (apex to specific outlets)

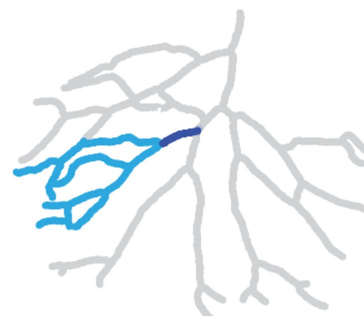


$(D - A)\cdot v_i = 0$ => Each v_i represents a different sub-network
Degree Matrix D (N x N): Diagonal matrix with d_{ii} = number of li
directly downstream from i.

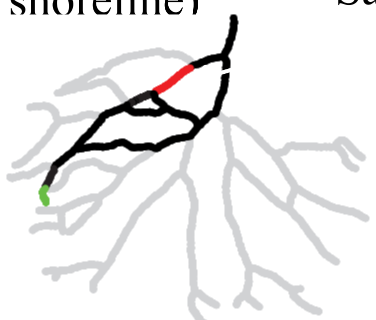
2. **<u>Find Downstream Regions of Influence</u>** of a link k, R_k.

$$(D_k - A_k)\cdot v_{k,i} = 0 \quad \Rightarrow \quad R_k \equiv \bigcup \left\{ v_{k,i} \mid v_{k,i}(k) \neq 0 \right\}$$

Union of all v vectors with non-zero entries at link k



3. **<u>Find 'hotspots' of change</u>** (links where a flux reduction would cause most drastic reduction at the shoreline)



Same reduction applied to different links

Causes different reductions at the same outlet

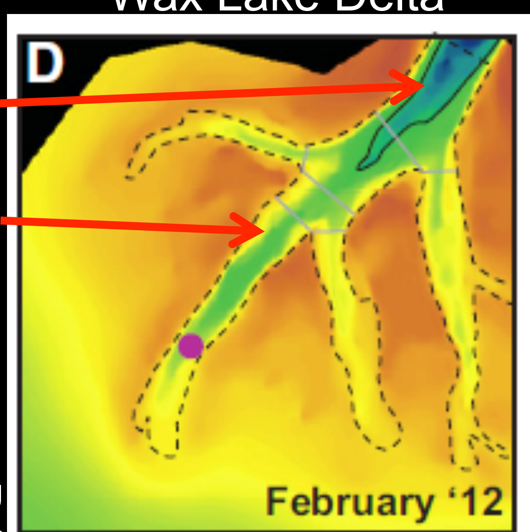
High reduction

Low reduction

Other Reduced Complexity Models

- A 1D delta restoration model
  - Team: Matt Czapiga Gary Parker, Enrica Viparelli
  - Treatment of alluvial-bedrock and bedrock-alluvial transitions in low-slope sand-bed rivers

Wax Lake Delta



stiff bay mud

alluvium

Shaw and Mohrig 2014

Exner equation for bedrock-alluvial and purely alluvial morphodynamics:

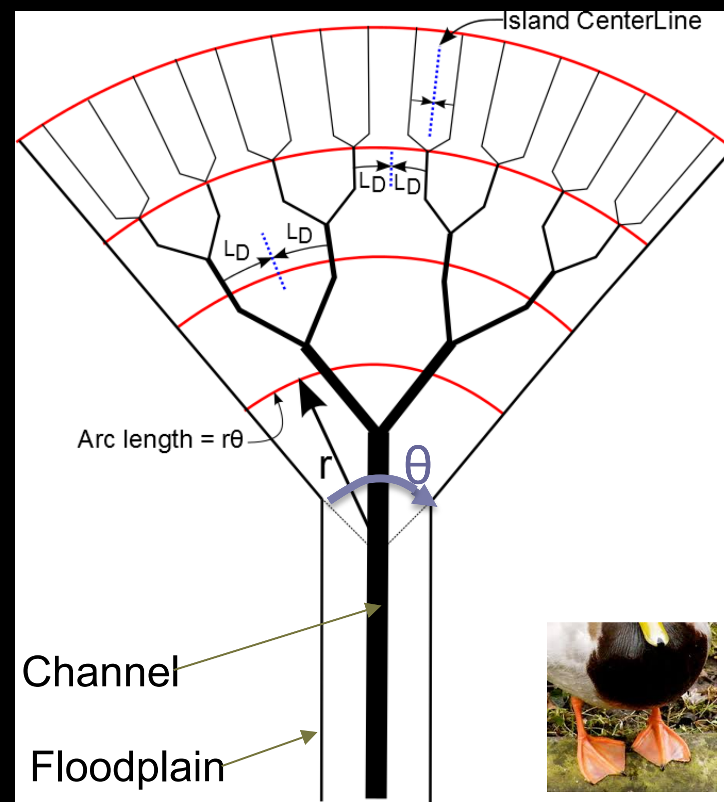
p_c = areal fraction cover of alluvium
q_{tc} = capacity sed. transport rate/width
η = bed elevation
λ_p = alluvial porosity

$$(1-\lambda_p)p_c \frac{\partial \eta}{\partial t} = -\frac{\partial p_c q_{tc}}{\partial x}$$

Other Reduced Complexity Models

- An Implicit 2D Delta Model: The Depositional Web

New self-formed channel closure:
Each channel deposits a width L_D to left and right, $L_D = \varphi B_{bf}$ (hence the web); B_{bf} = bankfull width, φ can be partitioned for sand and mud.



Number of channels λ varies continuously, so channels are implicit:

$$\lambda = \frac{\theta r}{B_{bf}(1+2\varphi)}$$

Closure finished with bifurcation relation similar to Edmonds and Slingerland (2008)

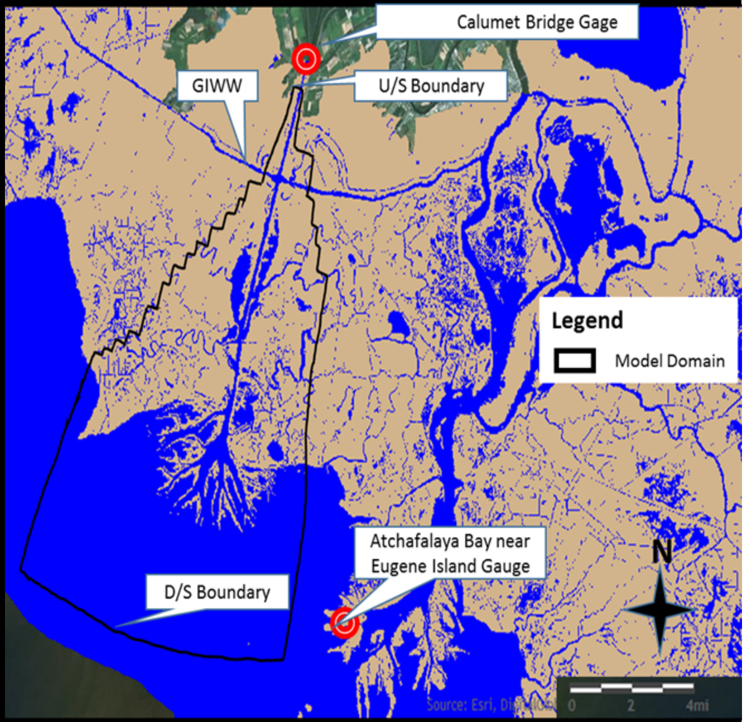
$$\frac{d\lambda}{dr} = \frac{\lambda}{L_B} \quad , \quad L_B \sim \frac{H_{bf}}{S_f} ,$$ where L_B = length to bifurcation

Multidimensional Ecomorphodynamic Models

- Current open-source, state-of-the-art in 3D delta morphodynamic modeling:
  - Delft3D-FLOW Version 6.00.00.2367 http://www.deltares.nl/en or http://csdms.colorado.edu/wiki/Model:Delft3D
- Example: Caldwell Keynote earlier this morning
- Example: Flow and sediment routing through Wax Lake Delta
  - Team: Ehab Meselhe, Ben Roth, Ashok Khadaka
  - Objective: Investigate the interaction and feedback among hydraulics, morphology, vegetation, and nutrient loading

Multidimensional Ecomorphodynamic Models

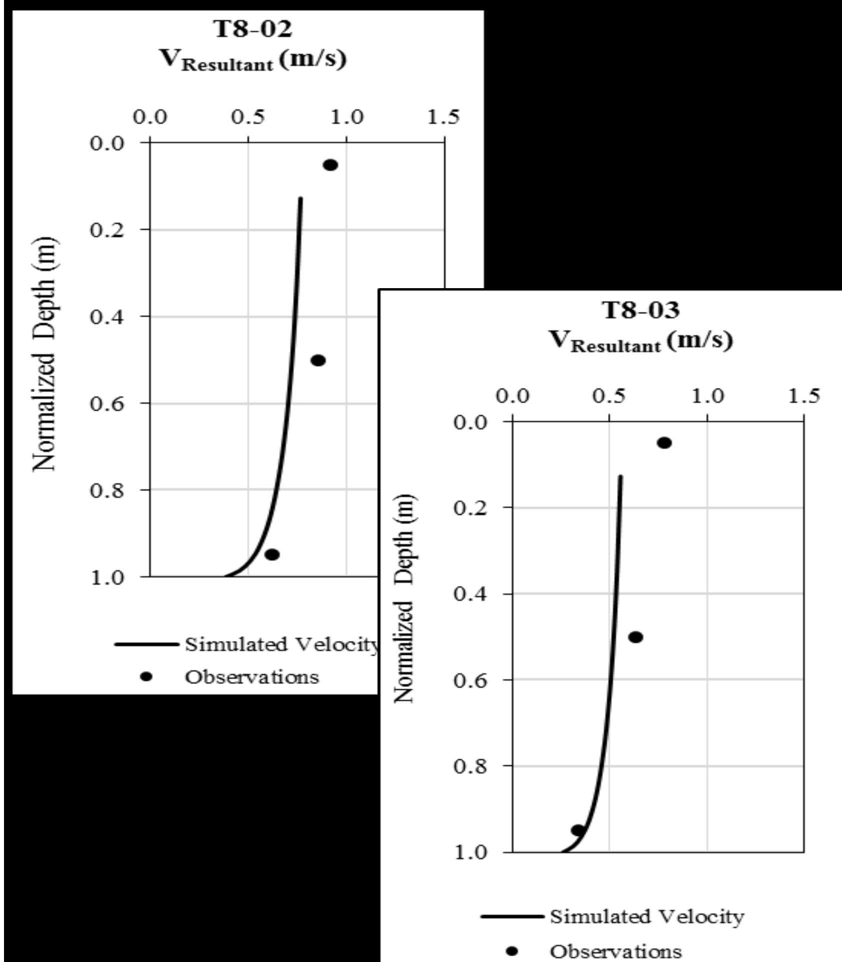
- Model Setup
  - Discharge and Sediment Inflow at Calumet Bridge Station
  - Stage/Tide at Atchafalaya Bay near Eugene Island
  - Orthogonal curvilinear grid with resolution 25m by 25m to 100m by 100m



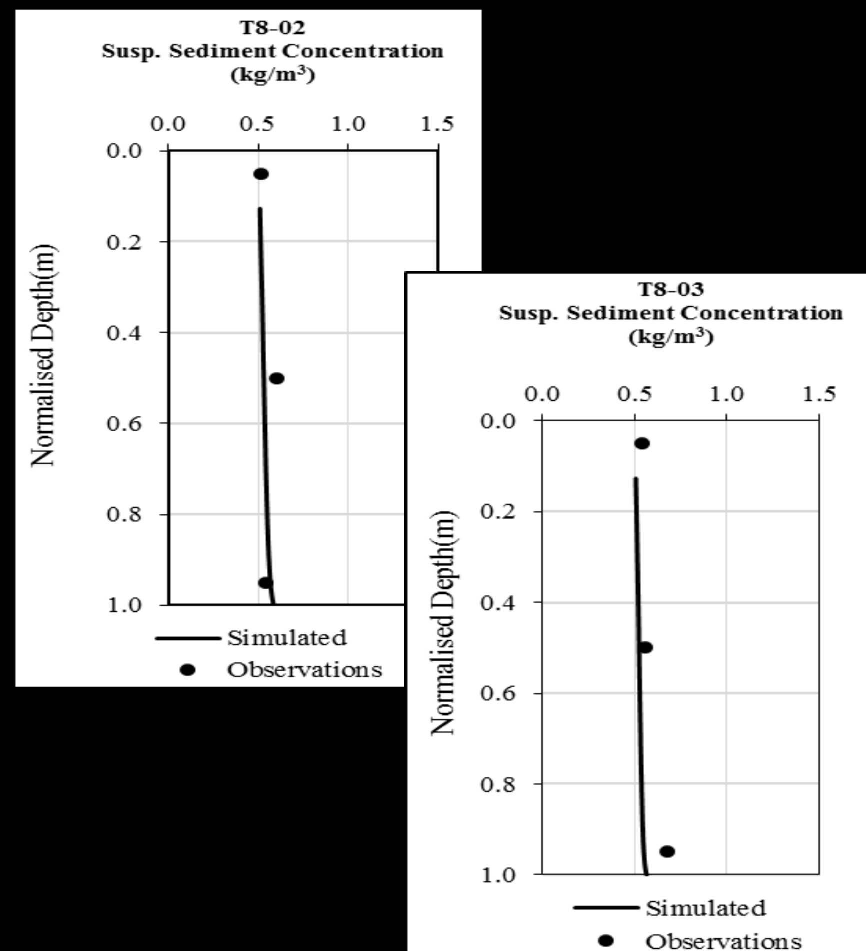
  - 10 sigma layers in vertical direction
  - Initial Bathymetry: USACE 1998 Hydrographic survey bathymetry & DDC lidar

Multidimensional Ecomorphodynamic Models

Vertical velocity profiles



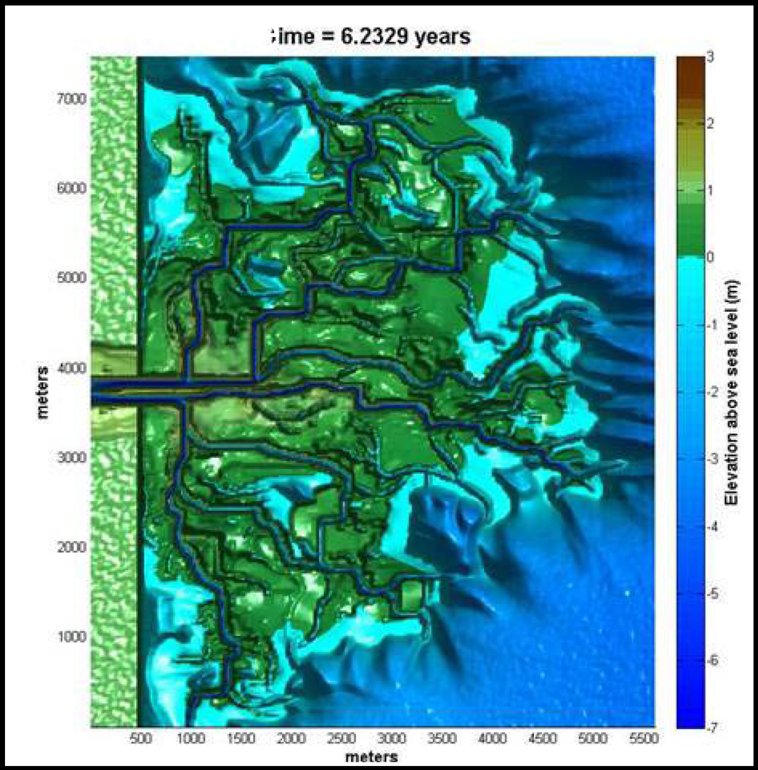
Suspended sediment profiles



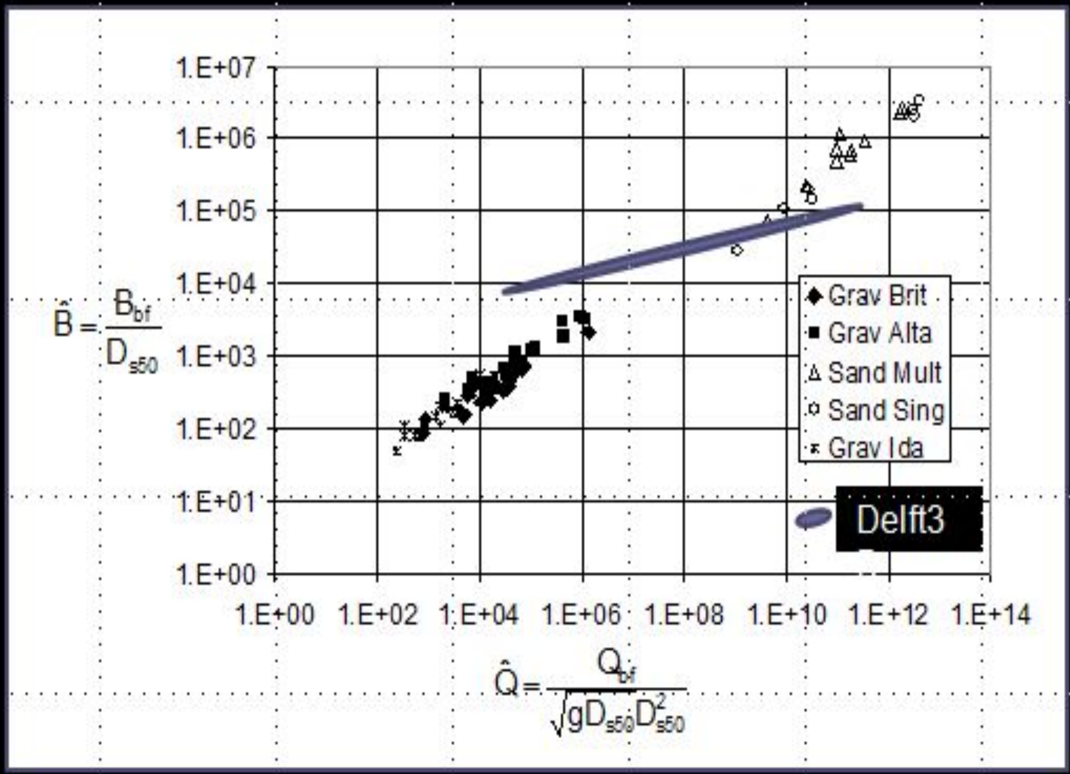
Multidimensional Ecomorphodynamic Models

- But there are problems……

1) morphodynamic simulations of deltas are an artifact of the underlying orthogonal grid



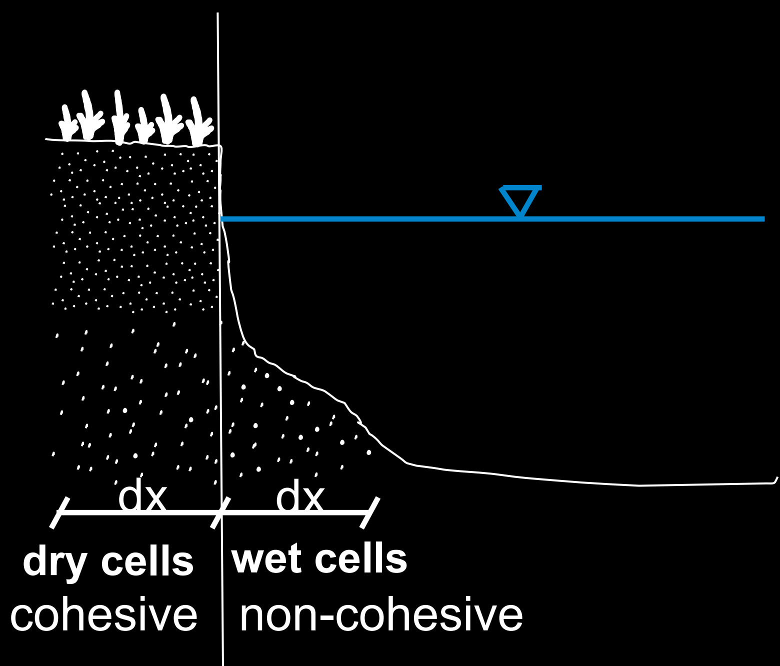
2) self-formed channel hydraulic geometries are inaccurate



Multidimensional Ecomorphodynamic Models

- Problems with current models (cont.)

3) the algorithms for eroding channel banks are *ad hoc*



4) the ecogeomorphic interactions are primitive

No dynamic vegetation with its effects on sediment trapping, turbulence generation, nutrient uptake

A New Multidimensional Ecomorphodynamic Model: D3D+

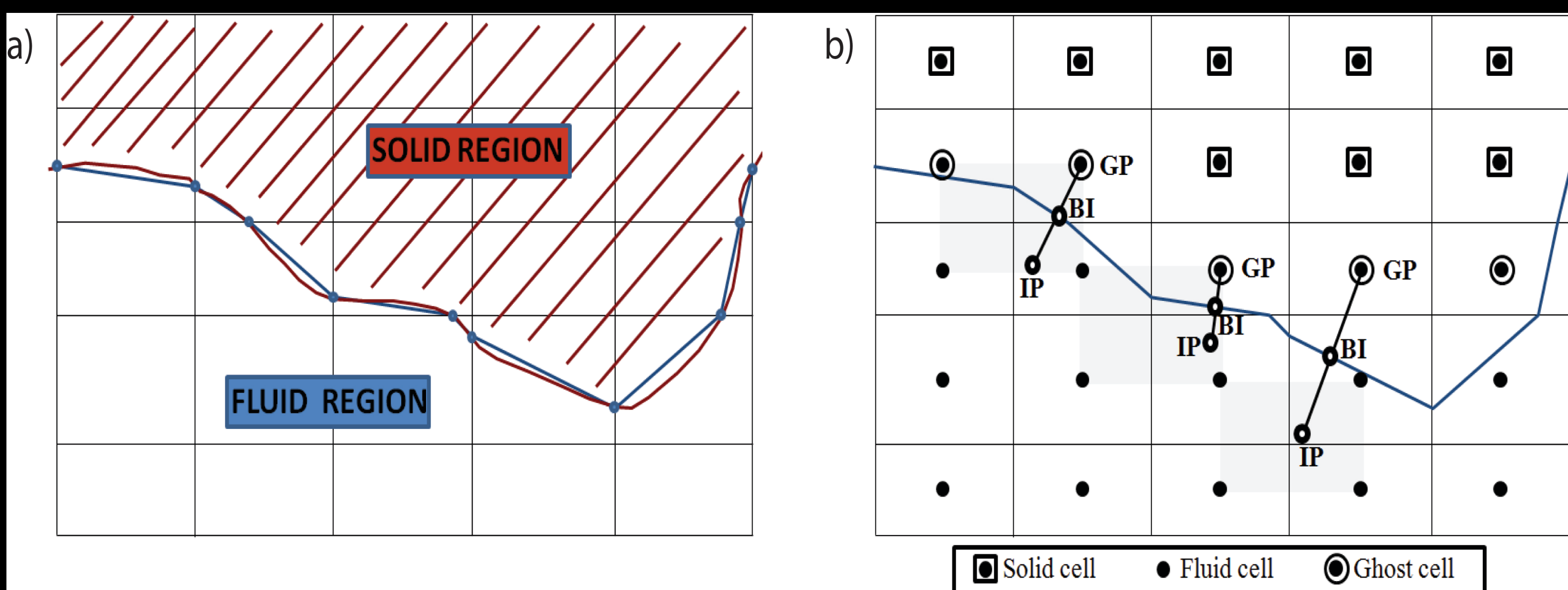
- A mass-conservative, staggered, three-dimensional, shallow water model

- Includes:
  - ghost-cell immersed boundary method for land/water boundaries
  - a sub-grid vegetation-flow interaction module

- Team: Alberto Canestrelli, Aukje Spruyt, Bert Jagers, Rudy Slingerland, Fei Xing, James Syvitski, Doug Edmonds, William Nardin

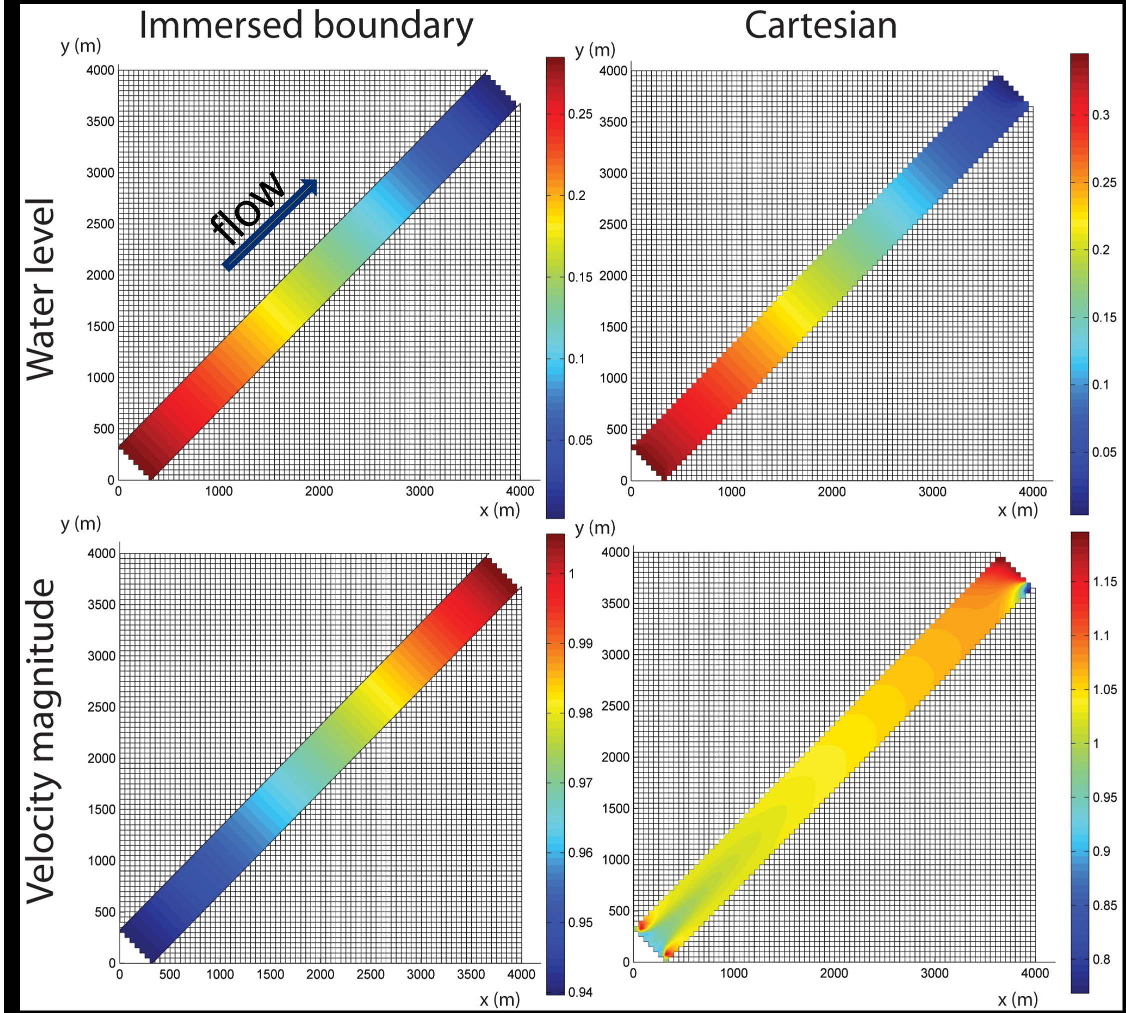
A New Multidimensional Ecomorphodynamic Model: D3D+

- Ghost cell immersed boundary method for land/ water boundaries
  - A hybrid cut-cell/ghost-cell method: ghost cells are used for the momentum equations
  - Cut-cells are used in the continuity equation in order to conserve mass

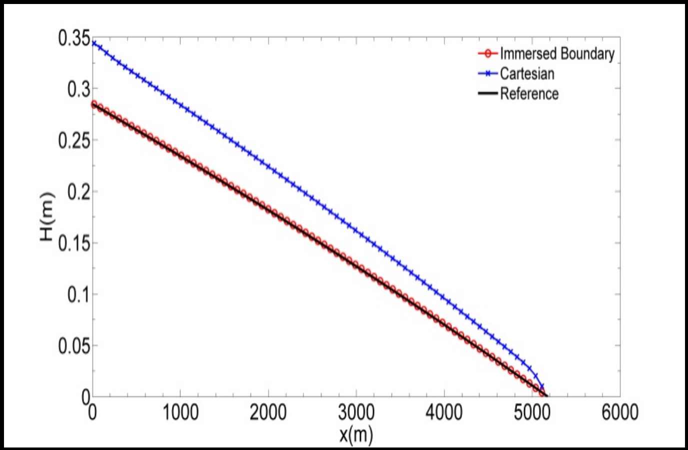


A New Multidimensional Ecomorphodynamic Model: D3D+

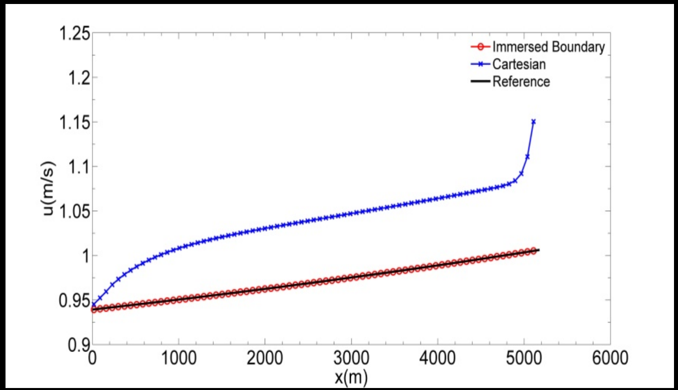
- Test Case: Flow in channel not oriented with grid



Longitudinal water level

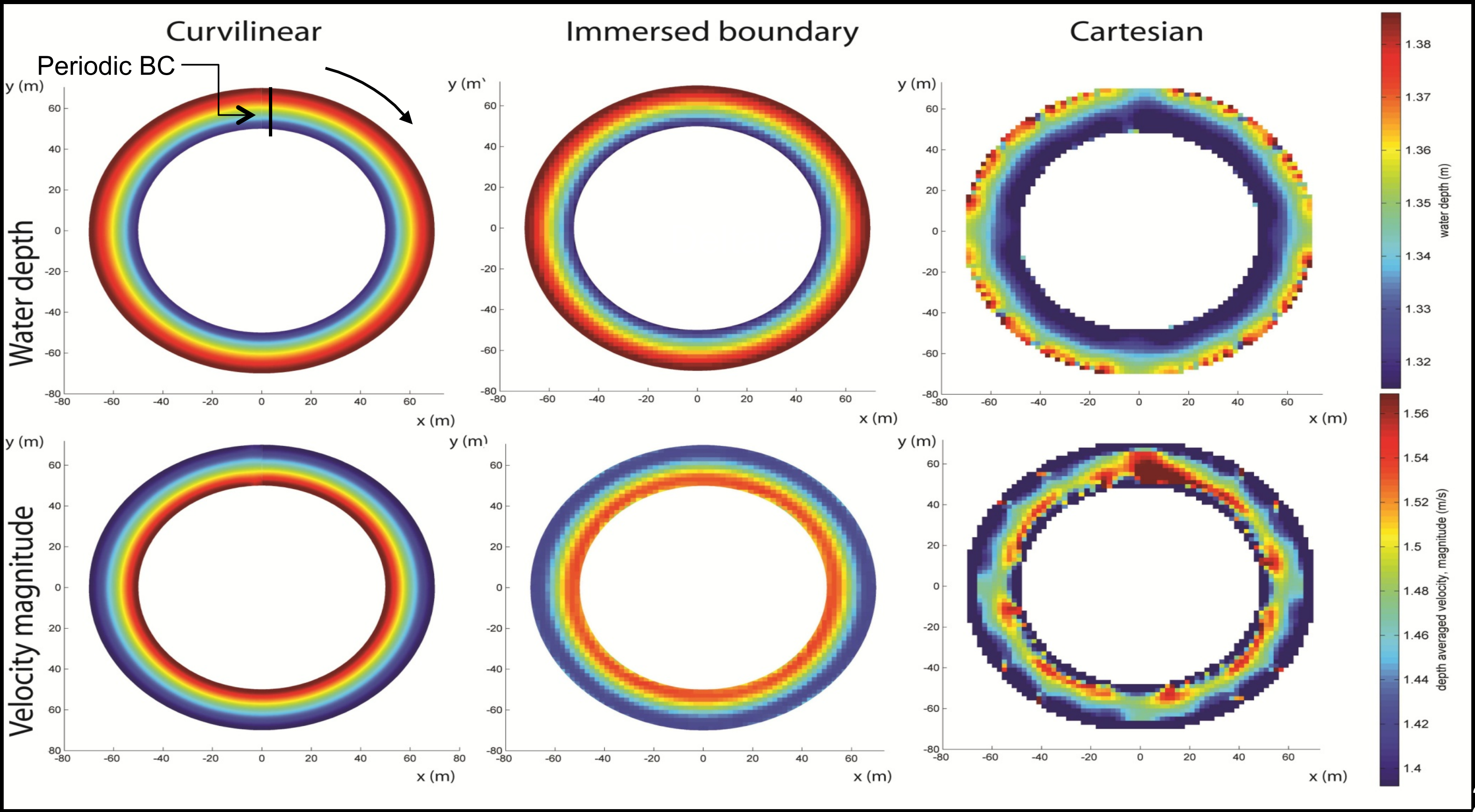


Longitudinal velocity



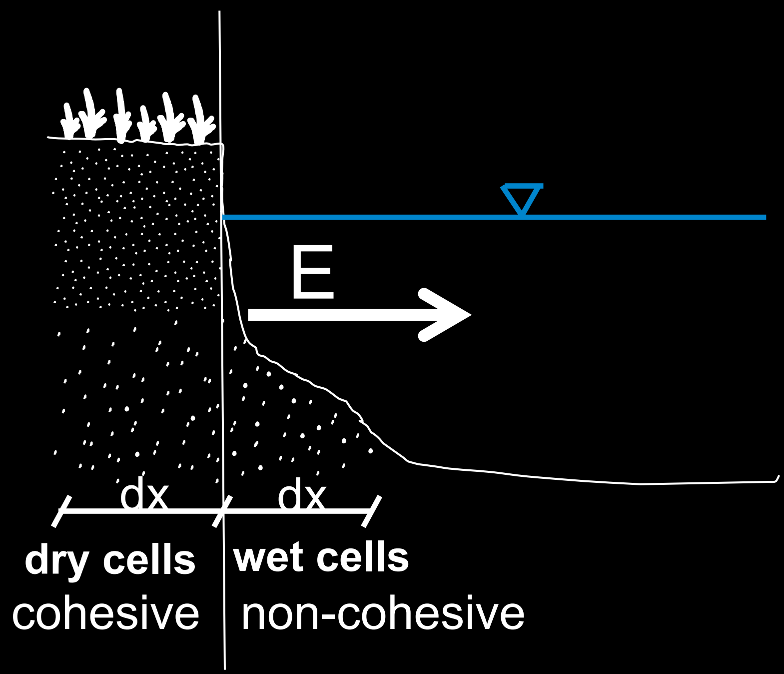
A New Multidimensional Ecomorphodynamic Model: D3D+

- Test Case: Flow in an infinite river bend



A New Multidimensional Ecomorphodynamic Model: D3D+

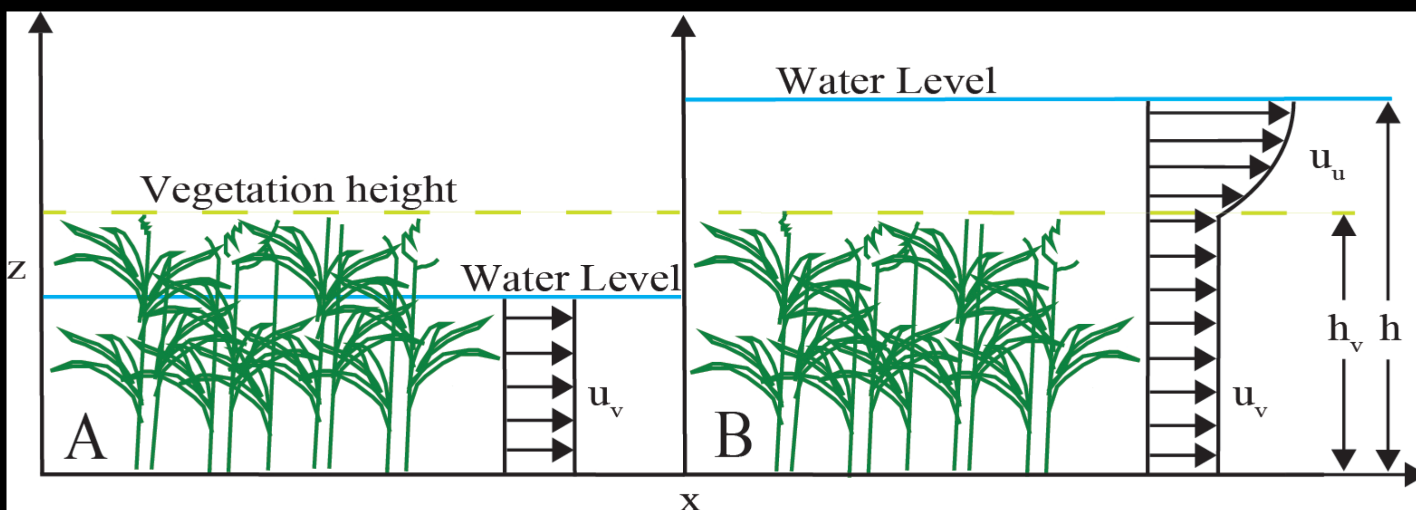
- A mass-conservative, staggered, three-dimensional, shallow water model
  - Can now treat lateral bank erosion…..
    - Use wall shear stress to predict particle-by-particle bank erosion (e.g. Darby & Thorne formulation)



$$E = k(\tau_b - \tau_c)^n$$

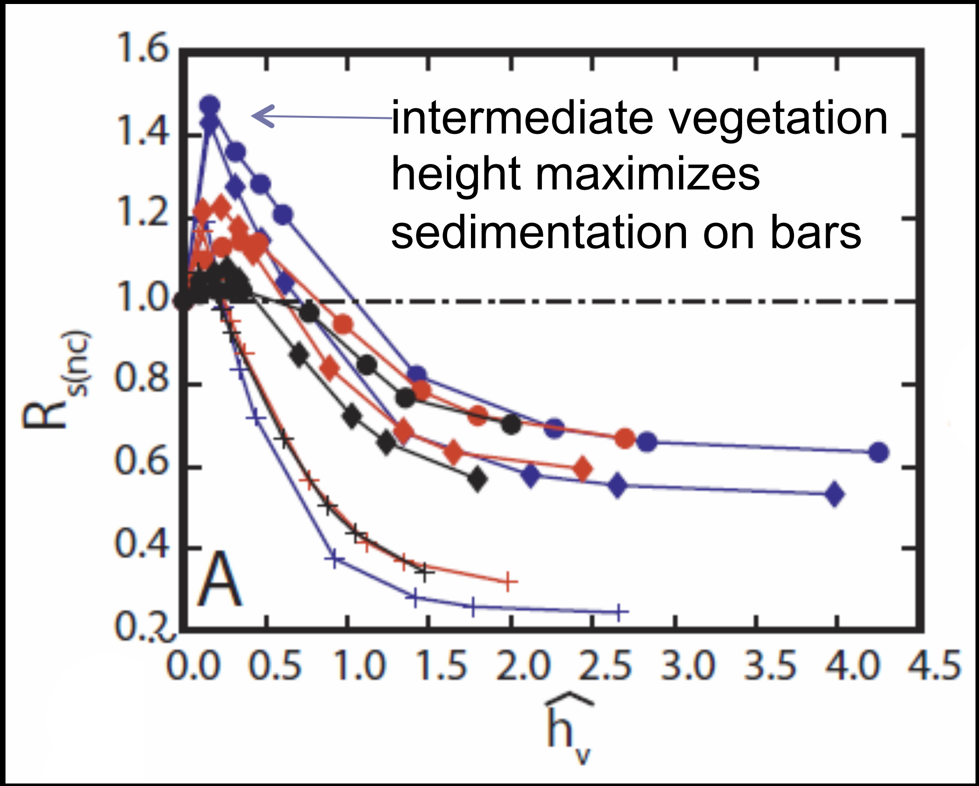
A New Multidimensional Ecomorphodynamic Model: D3D+

- A sub-grid vegetation-flow interaction module
  - based upon the Baptist et al. (2005) equations
    - Vegetation modeled as rigid cylinders characterized by plant height, density, stem diameter, and drag coefficient in the model.
    - Vertical flow velocity profile is divided into a constant zone of flow velocity inside the vegetated part and a logarithmic velocity profile above for submerged vegetation



A New Multidimensional Ecomorphodynamic Model: D3D+

- A sub-grid vegetation-flow interaction module
  - Results
    - Adding vegetation increases the *local fraction* of sediment deposited inside a marsh but…..
    - the vegetative roughness also forces more water into the channels, leading to more erosion in the channels and more water by-passing the marsh surface



$R_{S(nc)}$ = the ratio between vegetated and non-vegetated sand deposition

A New Multidimensional Ecomorphodynamic Model: D3D+

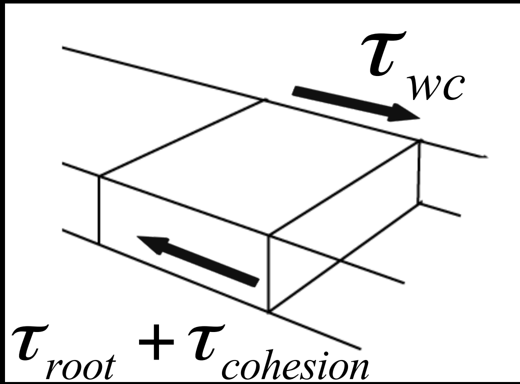
- A sub-grid vegetation-flow interaction module
  - Turf Erosion Module
    - A new module calculates the critical shear stress needed to rip up turf
    - Stress balance on a cube of turf…..

$$\tau_{wc} \geq (\tau_{root} + \tau_{cohesion})$$

where: τ_{wc} = wave-current shear

τ_{root} = root strength

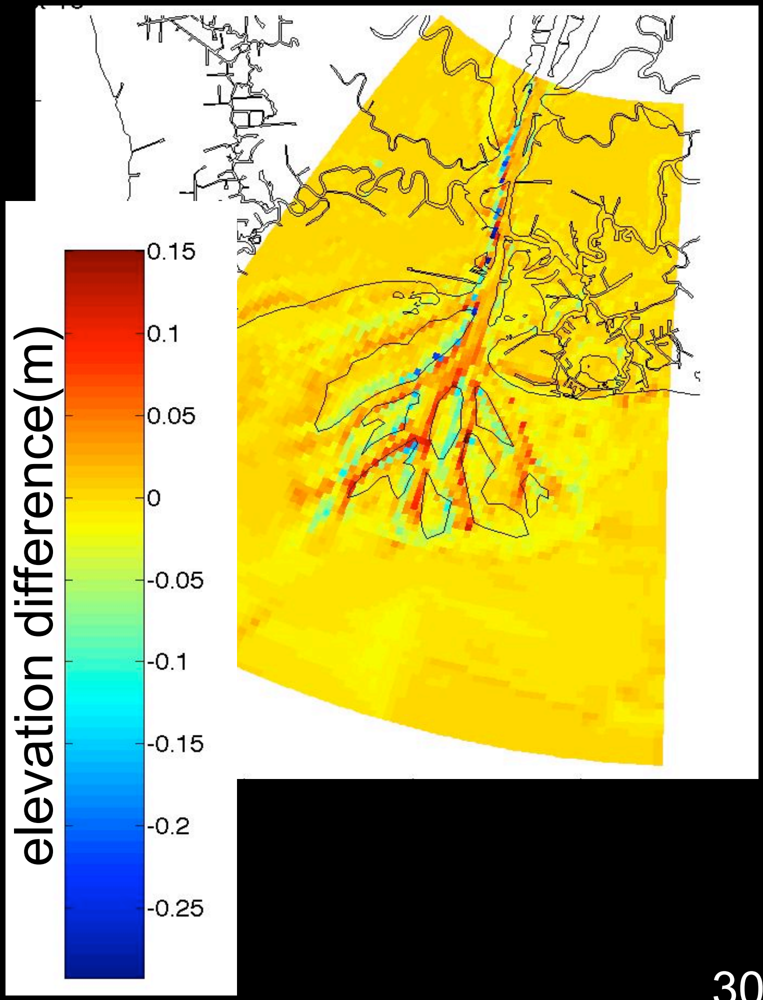
$\tau_{cohesion}$ = sediment strength



- turf parameters are a 3D function

Numerical Scheme: Add a vegetation root routine in Delft3D model

- Turf Erosion Module
  - Application: Wax Lake Delta during Hurricane Rita in 2005
  - Delft3d Flow + SWAN wave model yields wave-current shear stresses
  - Figure: Predicted bed elevations at end of storm from original Delft3D - predicted bed elevations from Delft3D with root module
  - Conclusion: can now quantify the amount that roots protect vegetated marshes from erosion

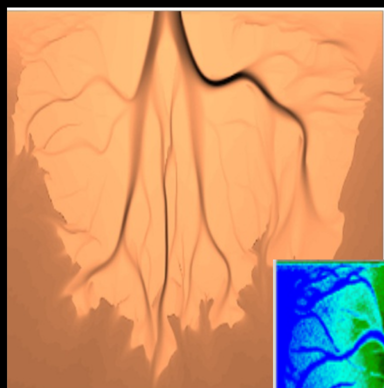


A New Multidimensional Ecomorphodynamic Model: D3D+

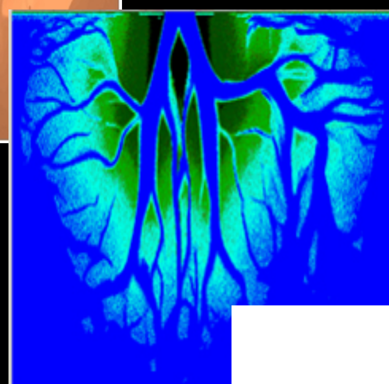
- An individual-based community model for predicting fish productivity on an evolving coastal delta
  - Team: Paul Venturelli, Manuel Garcia-Quismondo
  - Objectives
    - develop an individual-based community model to predict fish productivity on an evolving delta
    - determine the structural features of a delta that are highly correlated to fish productivity
    - develop a mechanism for evaluating alternative restoration scenarios in terms of fish productivity

A New Multidimensional Ecomorphodynamic Model: D3D+

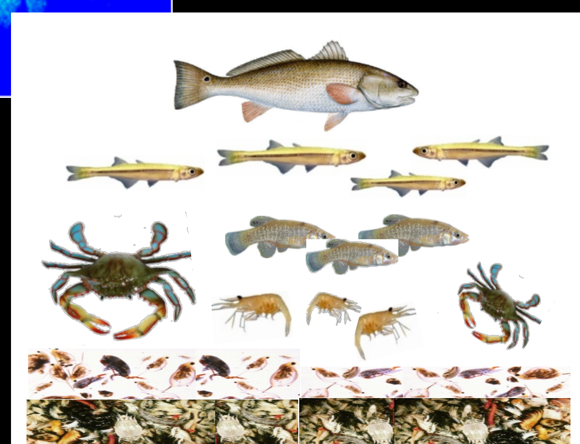
- An individual-based fish productivity cellular model



Layer 1: bathymetry
-1.8 x 10^6 cells, each 2 x 2 m
- DELFT3D output (Edmonds)



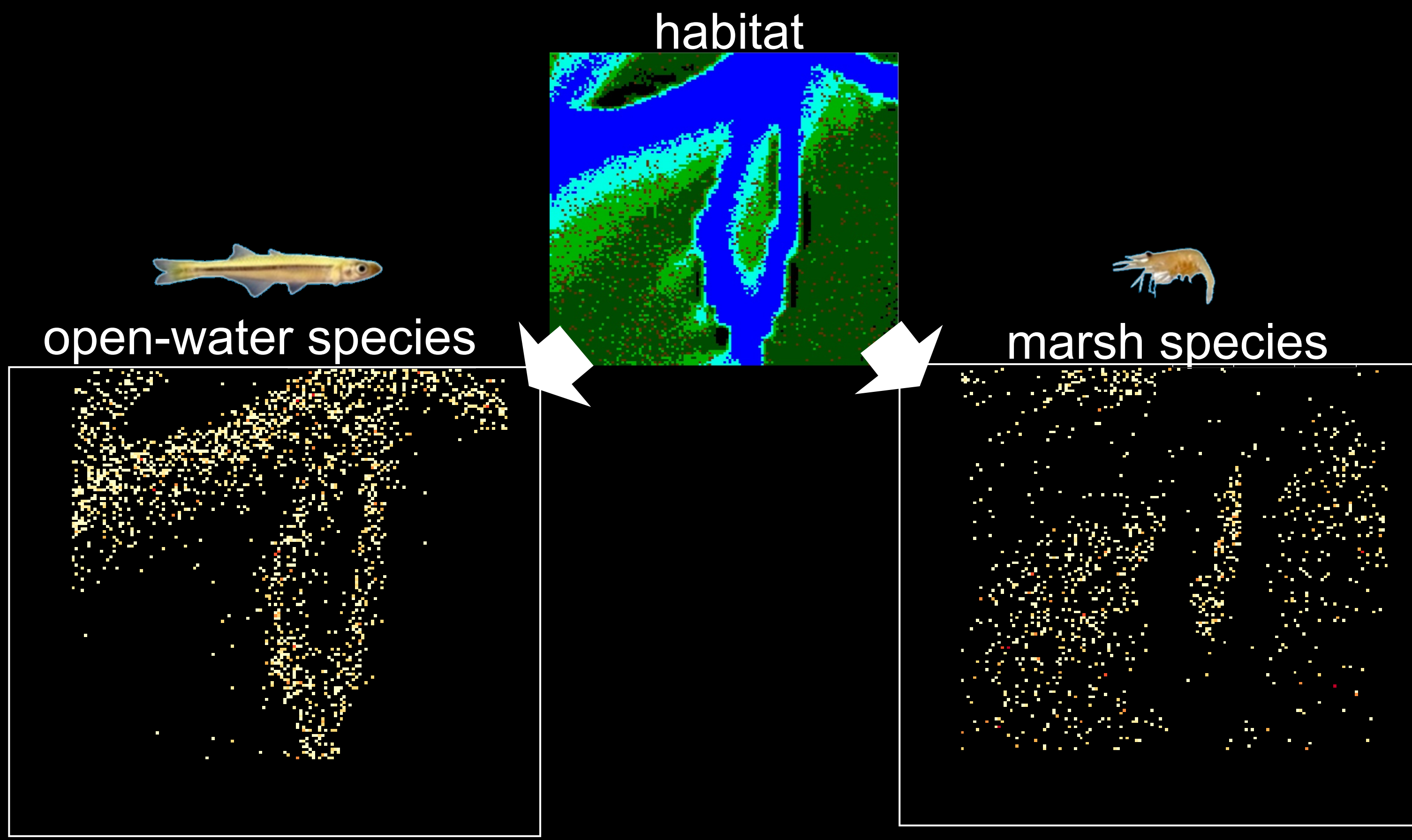
Layers 2 and 3: water and vegetation
- hourly water levels (from station data)
- vegetation (empirically-derived inundation rules)
- also temperature



Layer 4: individual-based fish model
- 400 x 400 m sub-grid
- 5 species
- Δt = 1 hour
- feed and grow
- swim about
- reproduce
- die

A New Multidimensional Ecomorphodynamic Model: D3D+

- An individual-based fish productivity cellular model
  - Results: snapshot of biomass distribution showing habitat associations



Summary Remarks

- As these models reach maturity in the next two years they will be further tested against Wax Lake data and incorporated into the CSDMS architecture and framework
- All models will be open source and made freely available via the CSDMS Repository
- If you have a specific immediate request please email sling@psu.edu.