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Simulating Environmental Changes Due to Marine Hydrokinetic Energy Installations

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Overview: Problems and Solutions

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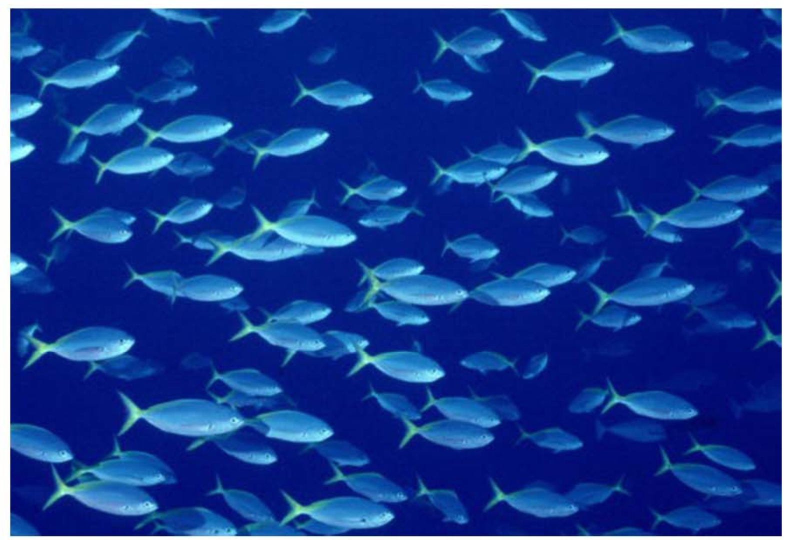
MHK Concerns

- Economic
  - Capital costs
  - Operation and maintenance
  - Power-generation efficiency
  - Environmental cost – ???
- Ecological
  - Volumetric flow/tidal range
  - Sediment dynamics
  - Water quality



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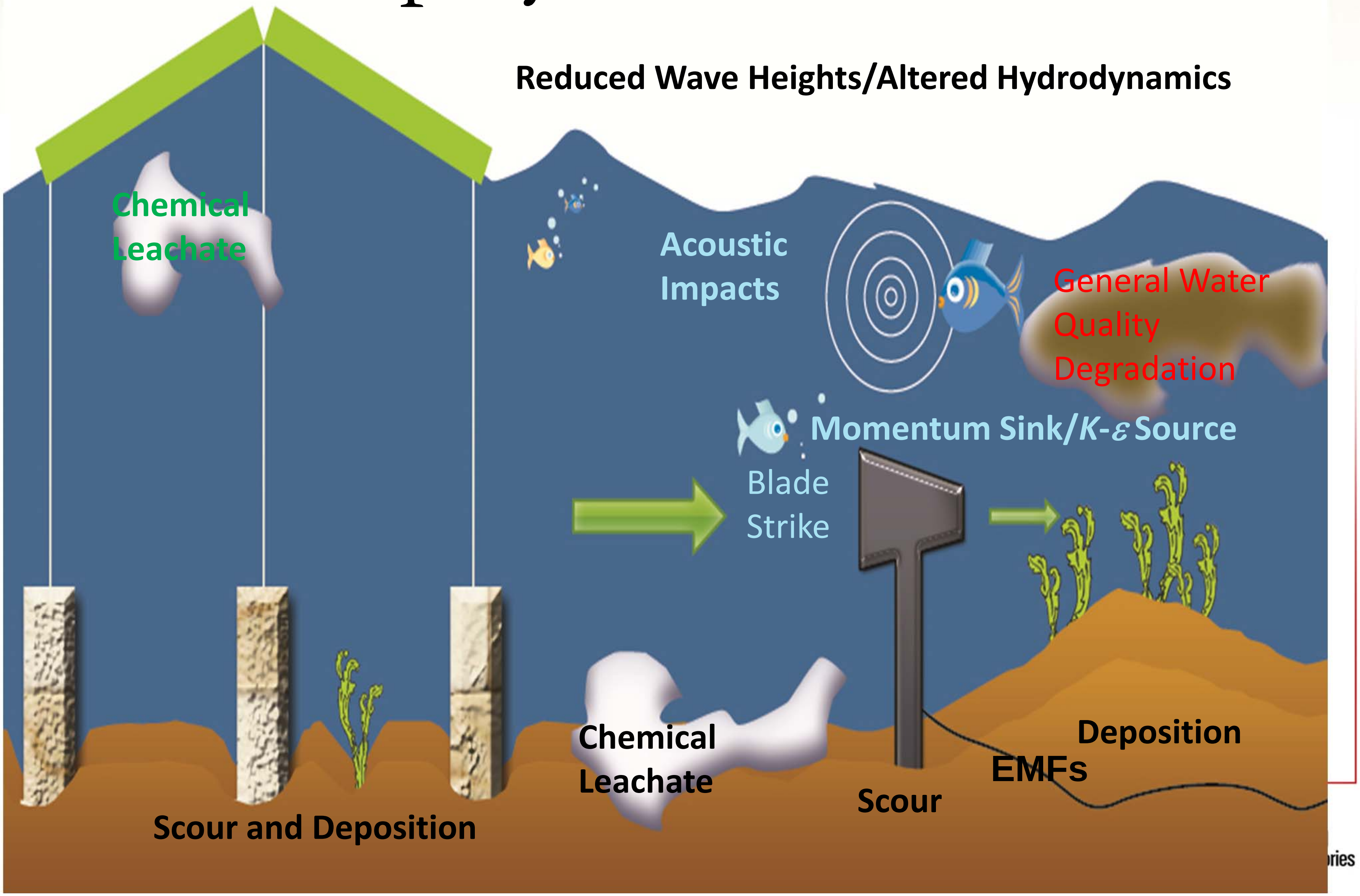
Environmental Effects of MHK Deployment



EFDC – Flow and Transport

- EPA open-source code (formerly, now with Tetra Tech)
- Curvilinear orthogonal grid
- Coupled-equation solution
  - Mass conservation
  - Momentum conservation
  - K-ε conservation
  - Temperature transport
  - Salinity transport
  - Dye transport

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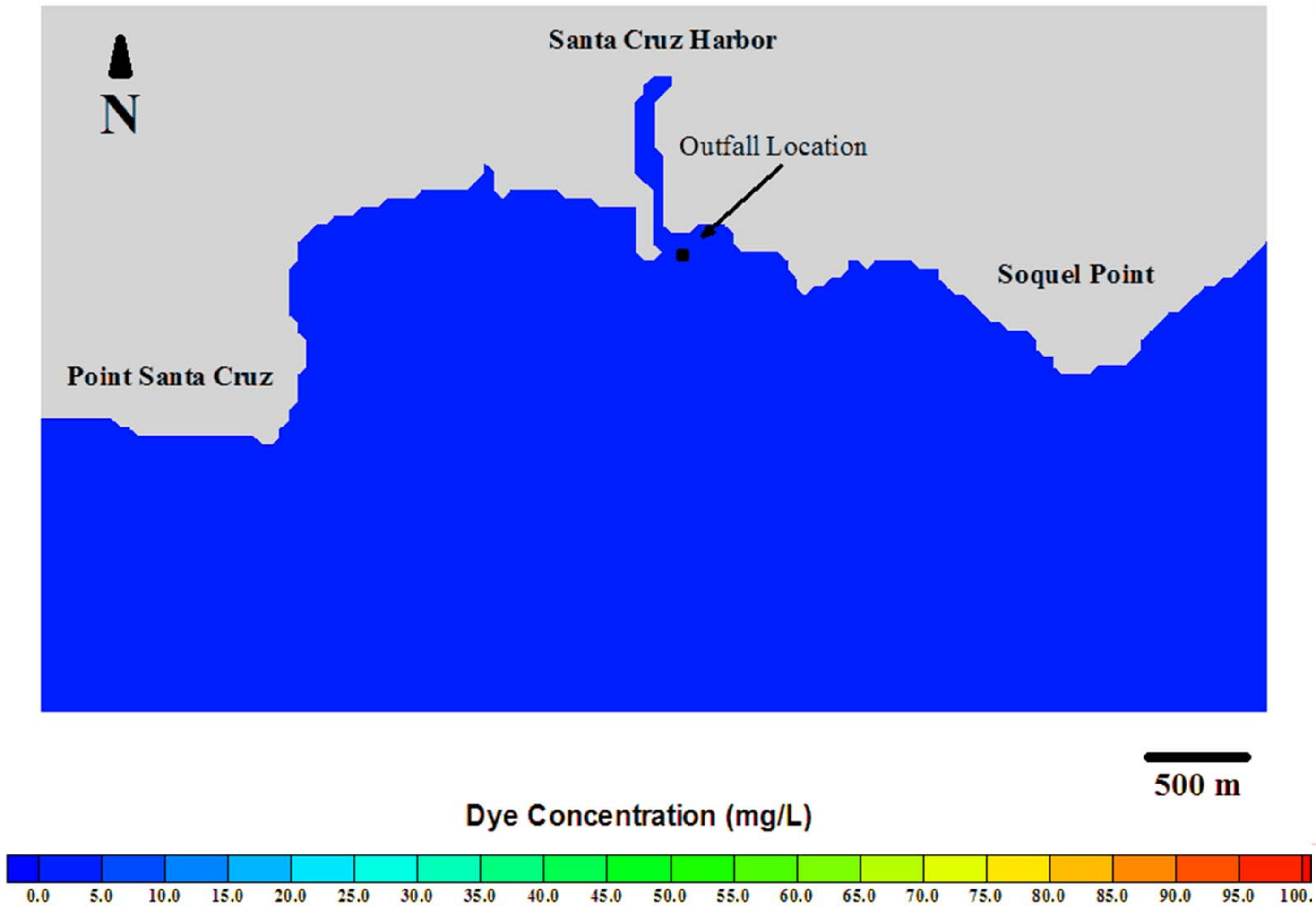
Flow Model – Santa Cruz



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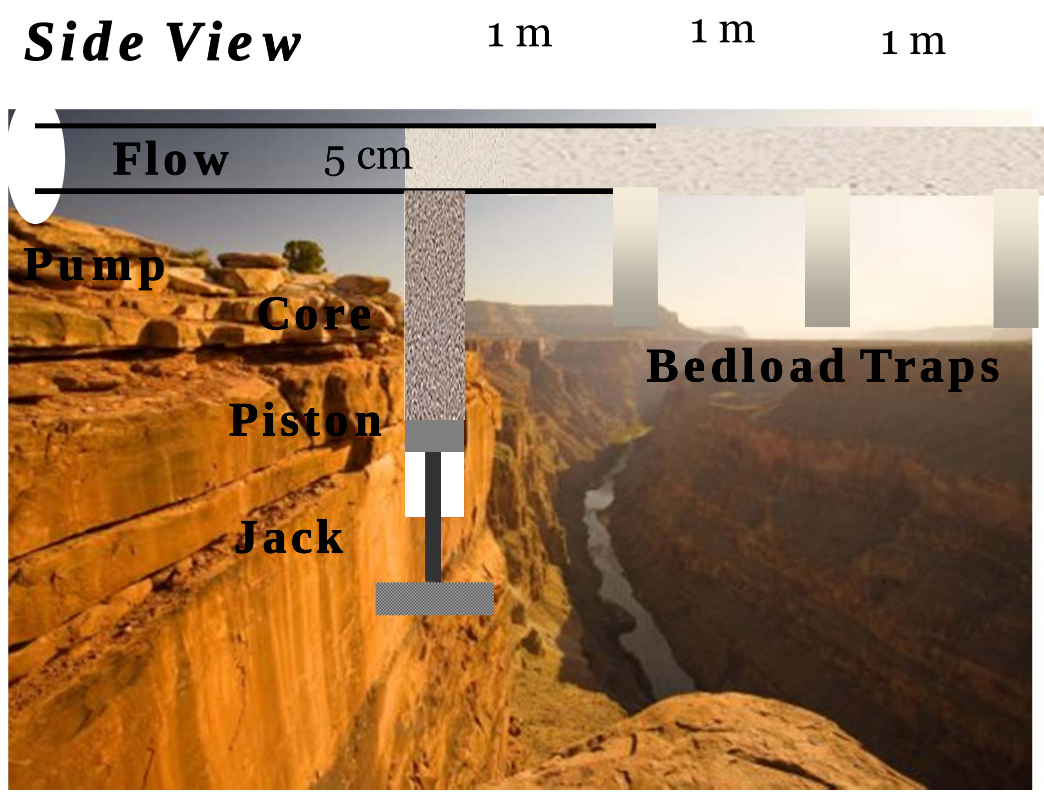
SEDZLJ – Sediment Dynamics

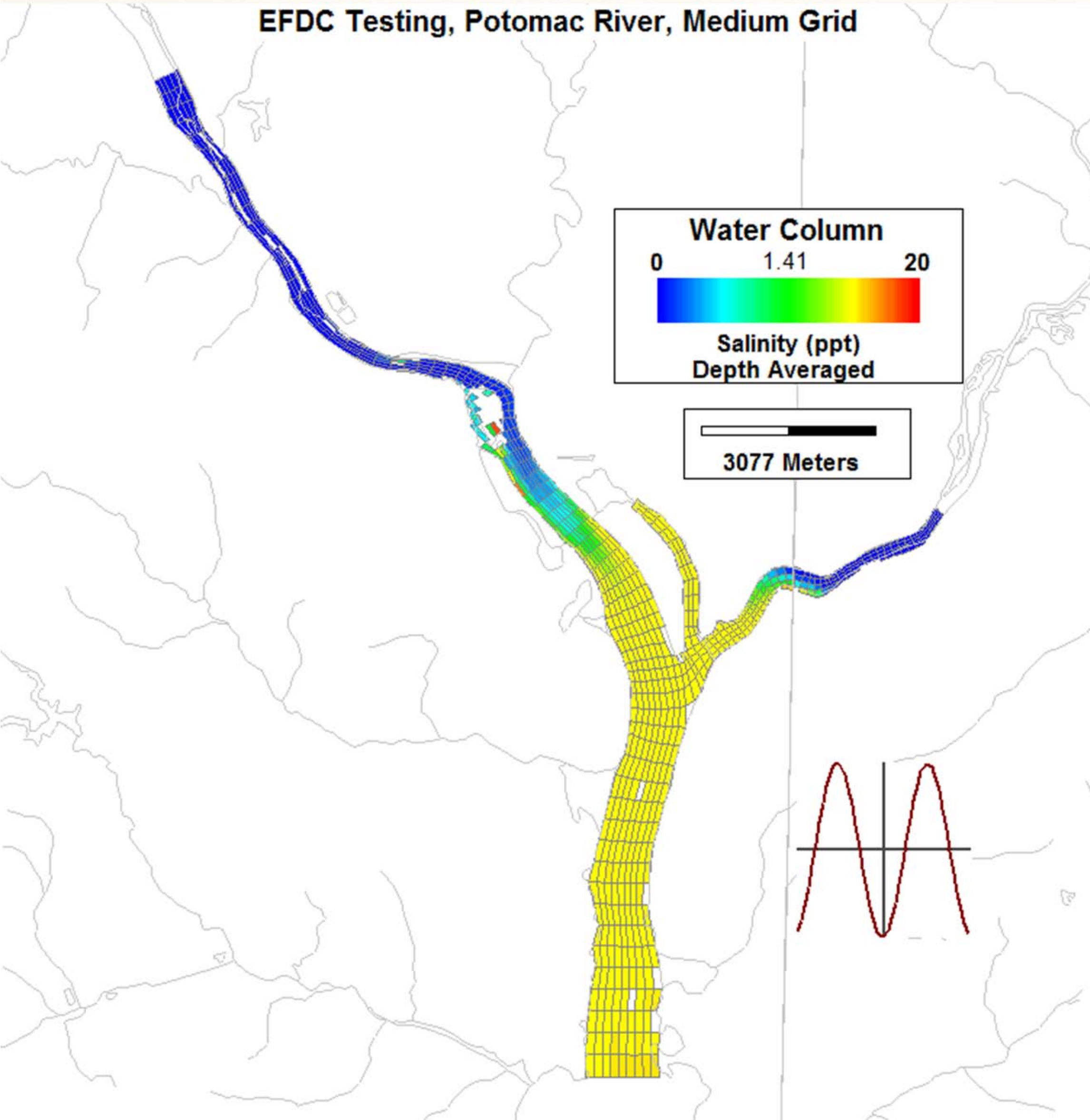
- Universal treatment of cohesive and noncohesive sediments
- Erosion based on site-specific SEDflume data
- Bedload and suspended load transport
- Bed-slope effects
- Bed armoring and consolidation



Sedimentment Model – Cedar Lake

Total Suspended Sediment Concentraion (mg/L)

CE-QUAL – Water Quality



- US Army Corps model
- 23 scalar water-quality parameters
- Kinetic reactions for:
  - Dissolved gases
    - O_2
    - CO_2
  - Algae growth
    - Cyanobacteria
    - Diatoms
    - Green algae
  - Nutrient cycles
    - Carbon
    - Nitrogen
    - Phosphorous
    - Silica

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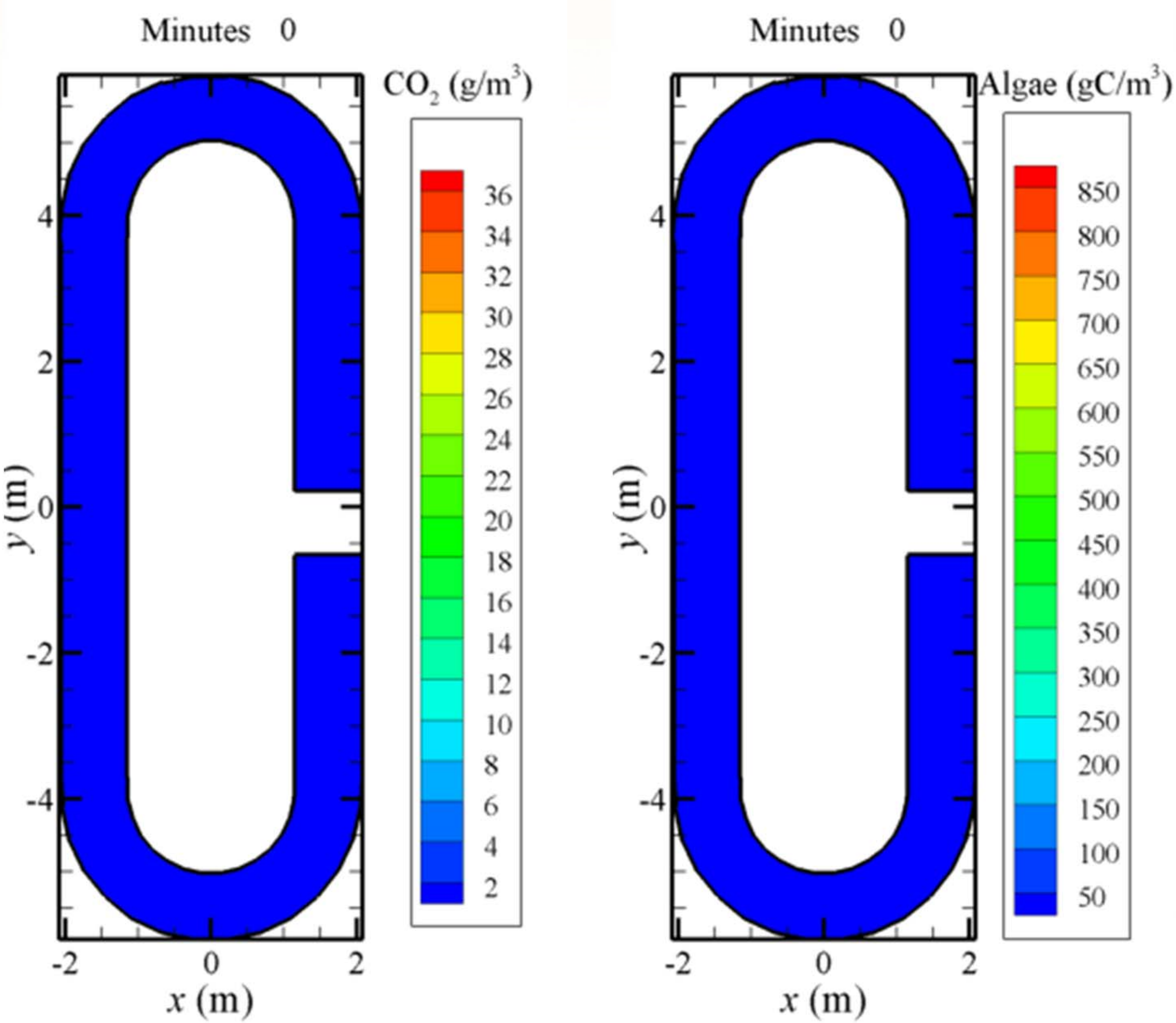
Water-Quality Model – Algal Raceway



MHK Energy Extraction

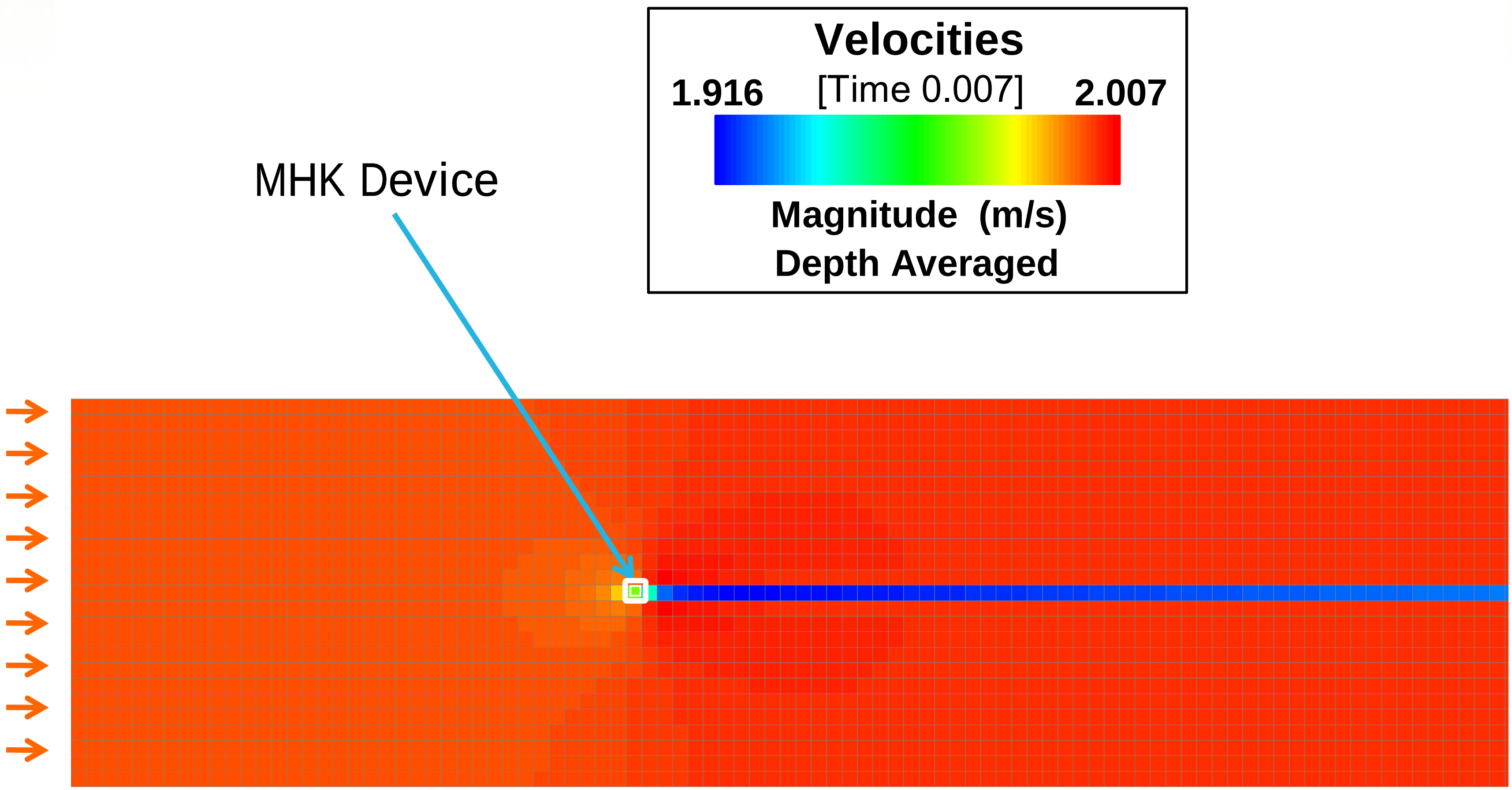
- MHK device energy extraction is manifest as
  - Decreased momentum
  - Altered (usually increased) turbulent kinetic energy
  - Increased turbulence dissipation rate (turbulent length scale)
- These quantities (momentum and K-ε) are advected and dispersed downstream

Momentum Sink

$$P_{\mathrm{MHK}} = \frac{1}{2} C_{\mathrm{T}} A_{\mathrm{MHK}} \rho U^{3}$$

$$S_{Q} = -\frac{1}{2} C_{\mathrm{T}} A_{\mathrm{MHK}} U^{2}$$

Single Turbine Model – Momentum Sink Only



- Overly persistent velocity defect

K—ε Modifications

Empirical constants

$$S_K = \frac{1}{2} C_{\mathrm{T}} A_{\mathrm{MHK}} \left(\beta_{\mathrm{p}} U^3 - \beta_{\mathrm{d}} U K \right)$$

$$S_\varepsilon = C_{\varepsilon 4} \frac{\varepsilon}{K} S_K$$

Katul, G. G., L. Mahrt, D. Poggi, and C. Sanz (2004), One- and two-equation models for canopy turbulence, *Boundary-Layer Meteorology, 113, 81-109*.

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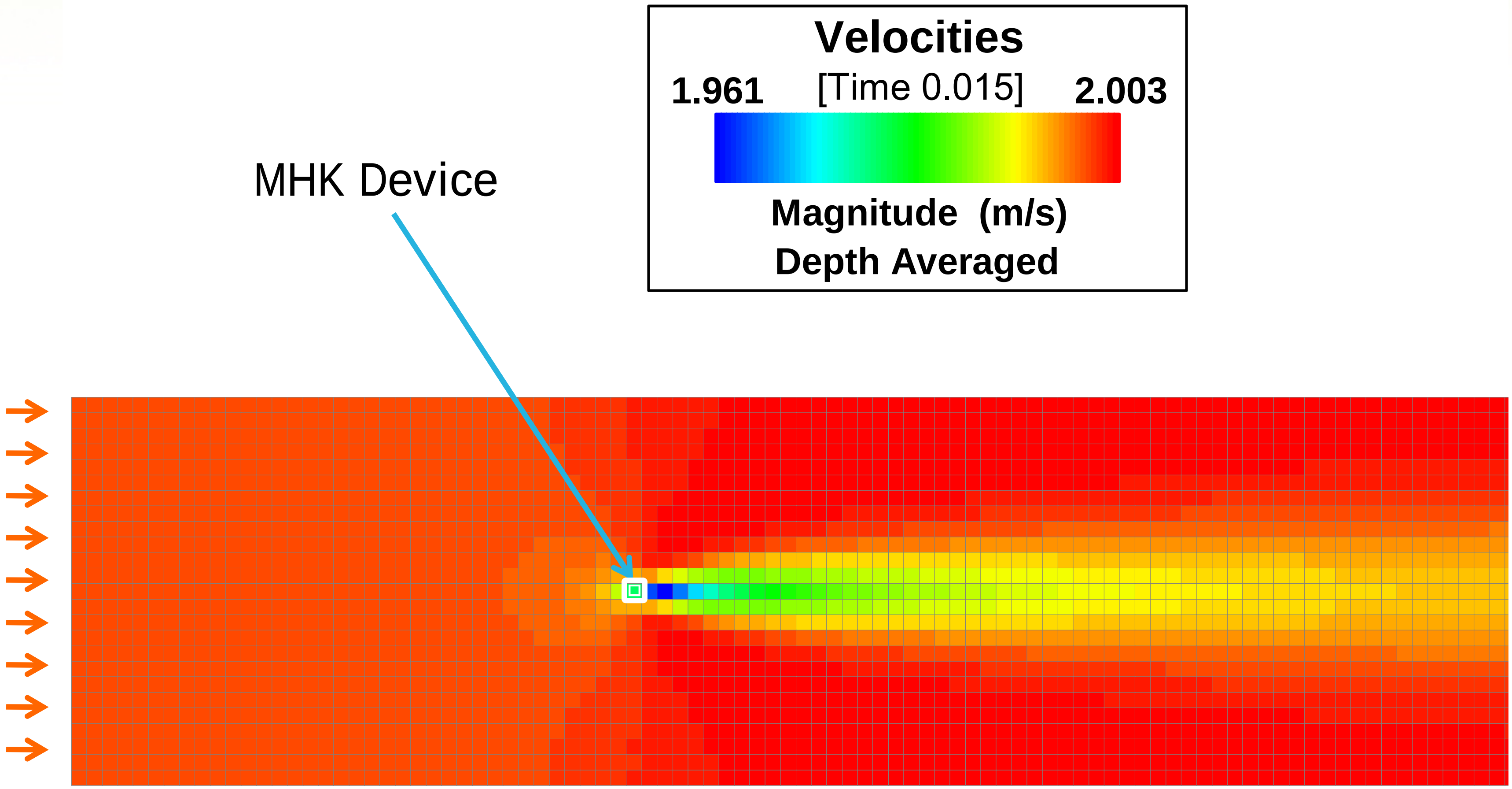
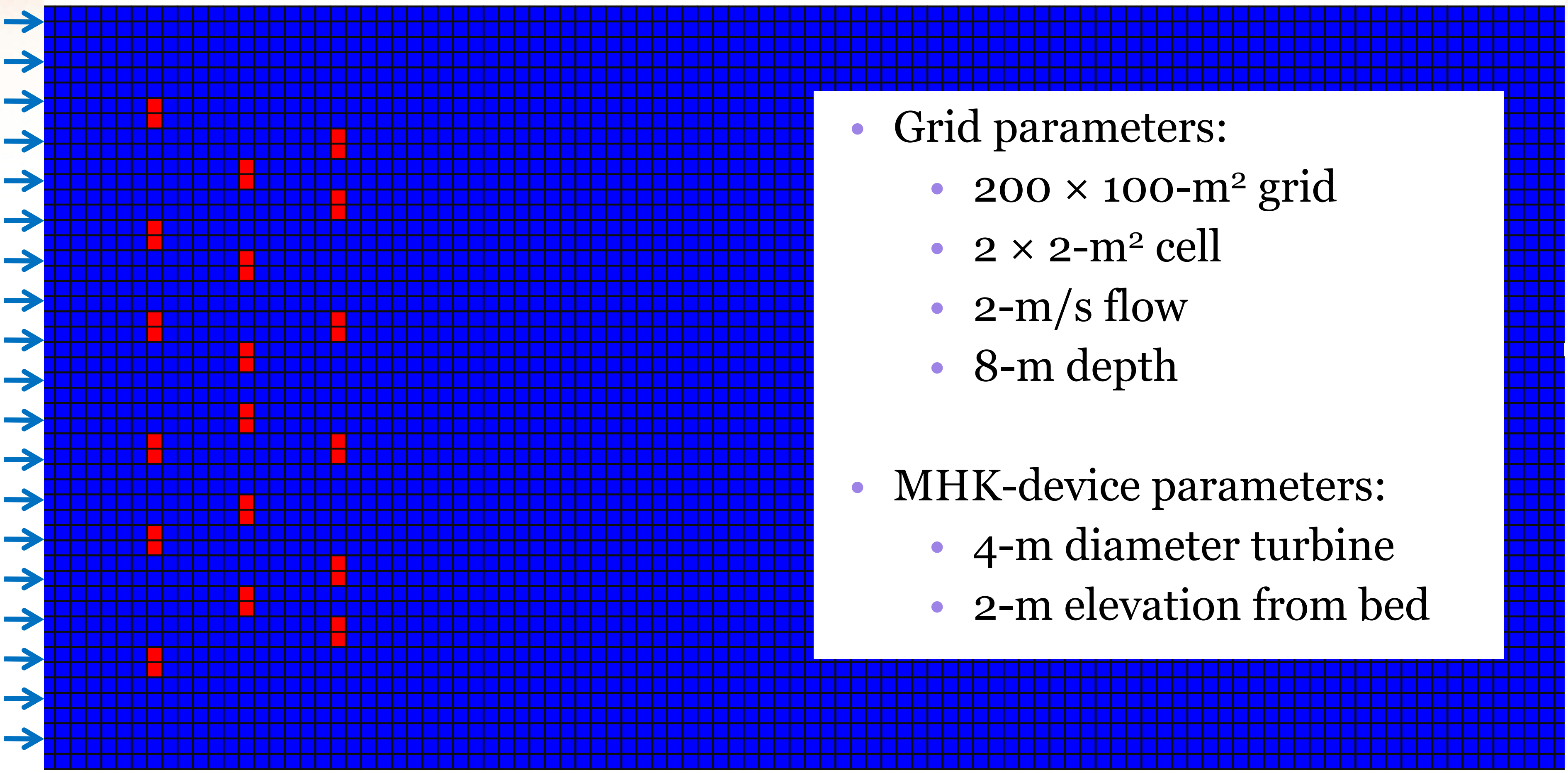
Single Turbine Model – K–ε Sources Included



- Realistic fluid energy loss/wake behavior

MHK Array – Device Locations



- Grid parameters:
  - 200 × 100-m² grid
  - 2 × 2-m² cell
  - 2-m/s flow
  - 8-m depth
- MHK-device parameters:
  - 4-m diameter turbine
  - 2-m elevation from bed

MHK devices: **red** cells

Hypothetical distribution to examine array behavior…

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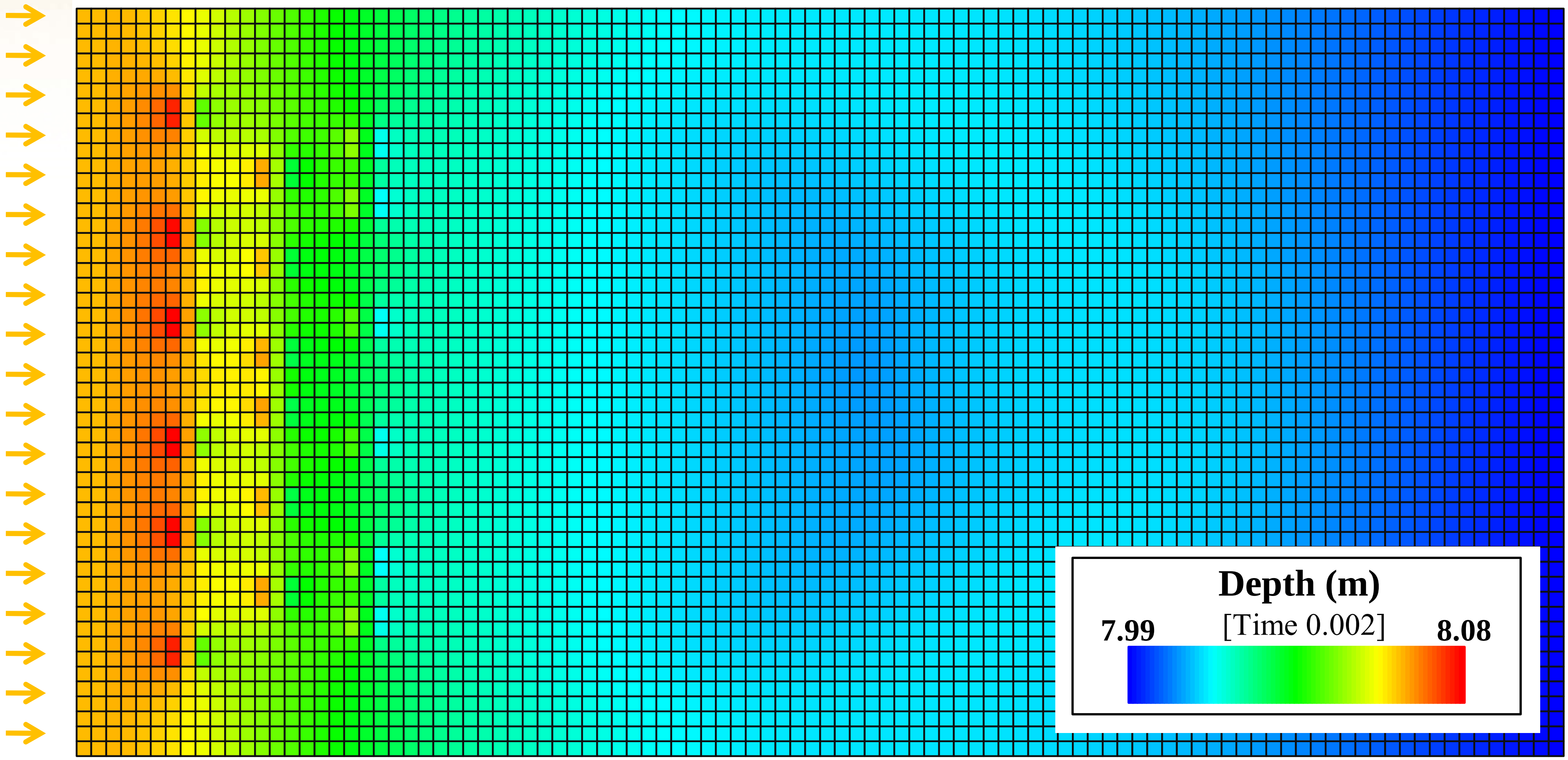
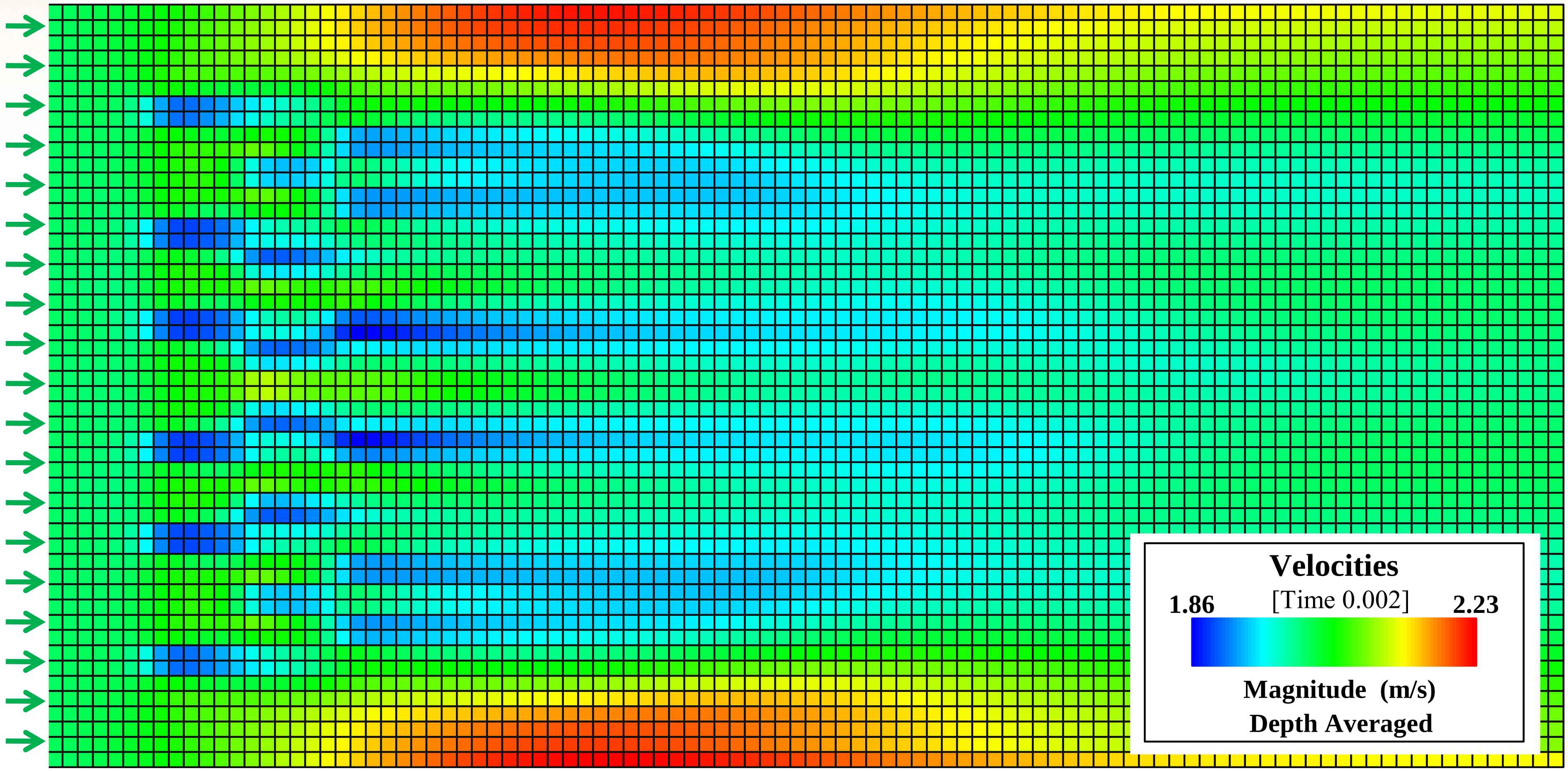
Water Depths



8.08 m (**red**) to 7.99 m (**blue**)

- MHK devices obstruct flow
- Fluid “back-up” and flow redistribution is evident
- Effects are most prominent in first row

Depth-Averaged Velocities



1.86 m/s (**blue**) to 2.23 m/s (**red**)

- MHK devices slow flow
- Diminishing returns – the first row extracts the most energy
- Flow seeks the path of least resistance

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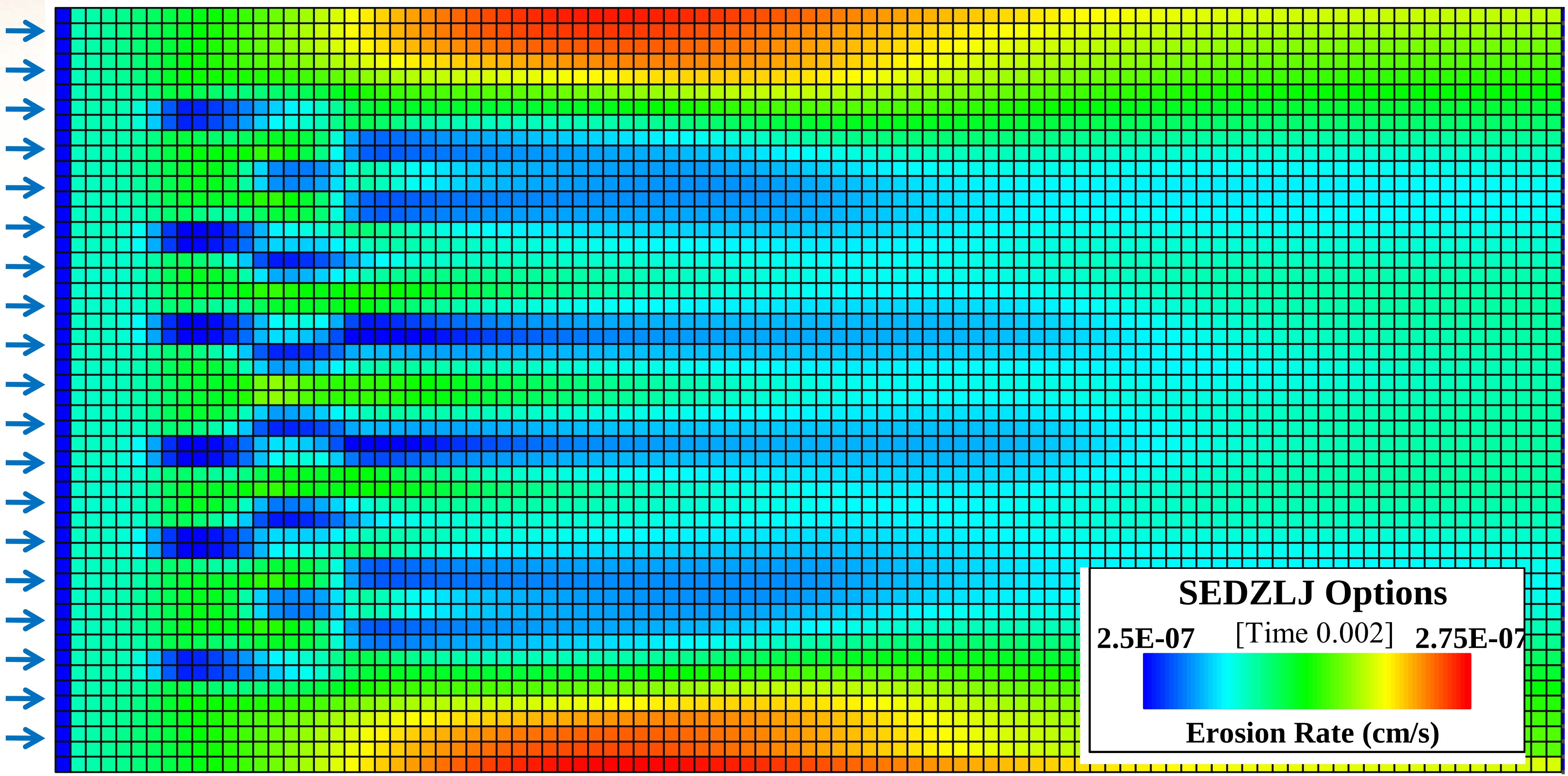
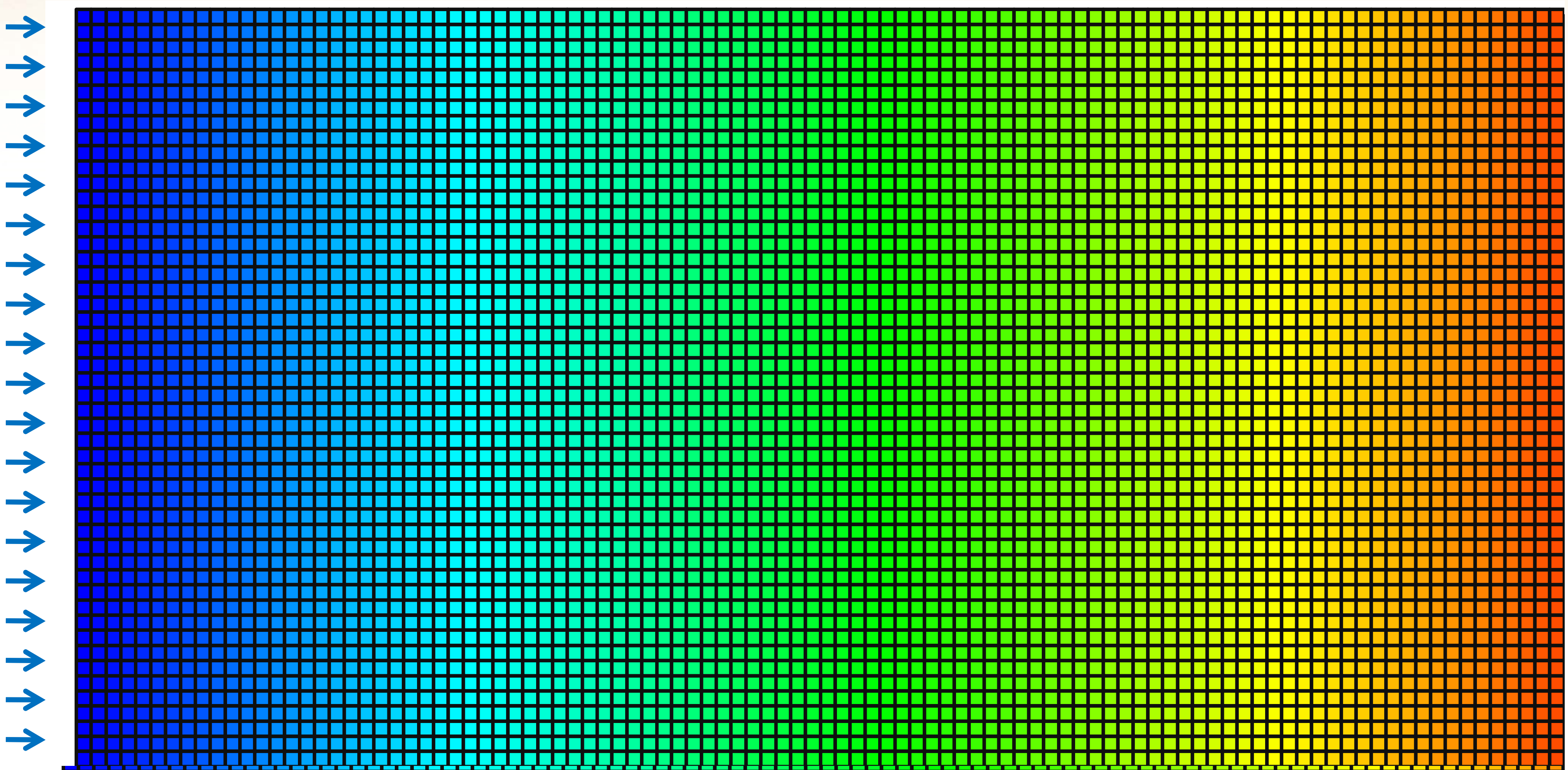
Erosion Rates



2.50×10^{-7} cm/s (**blue**) to 2.75×10^{-7} cm/s (**red**)

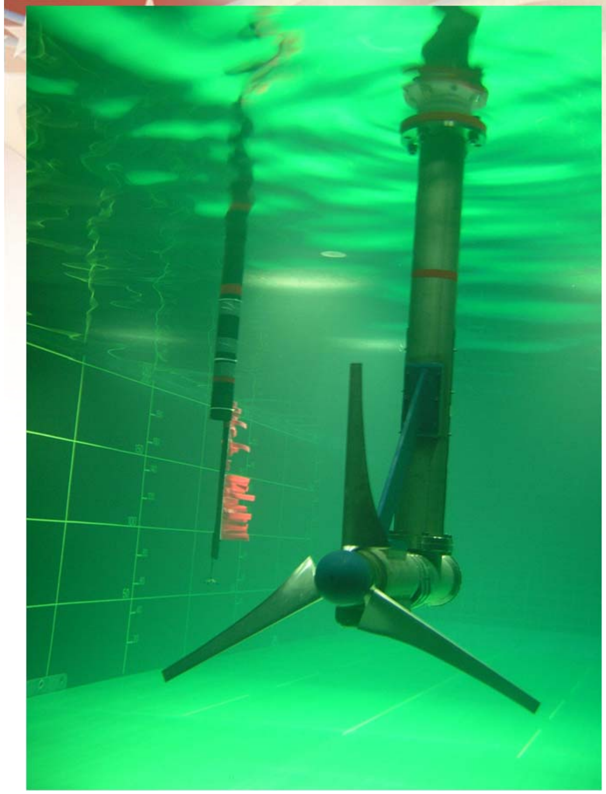
- Scouring patterns evident
- Benthic organisms may be sensitive to changing sediment composition

Water Age

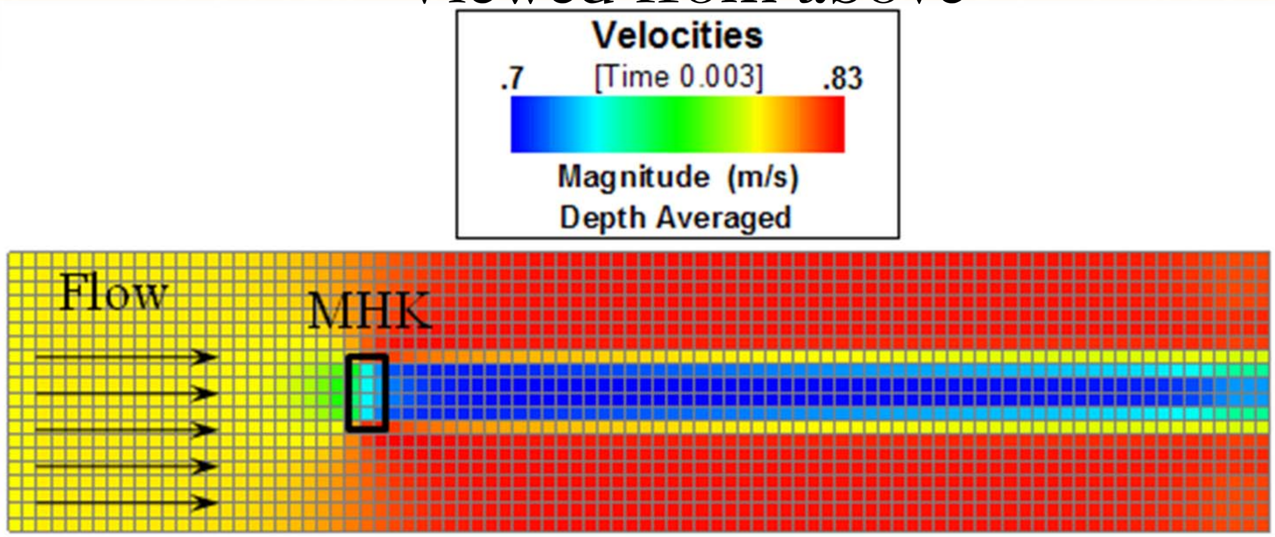


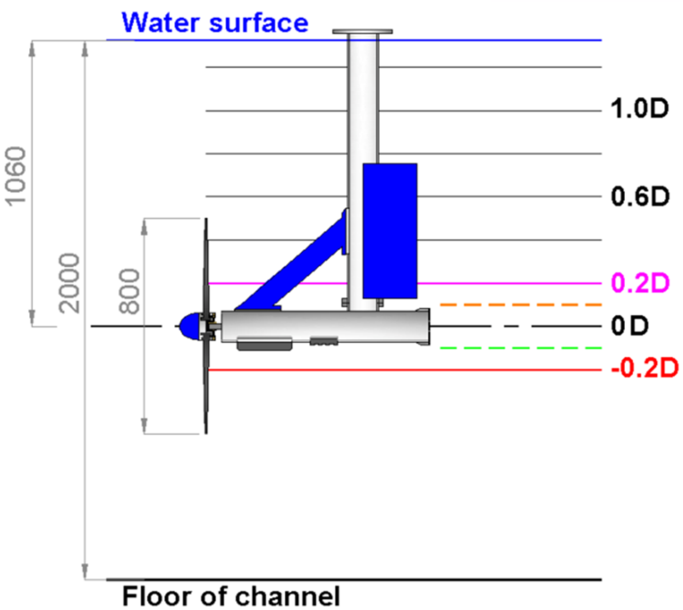
No Array

Model Verification



Viewed from above





Parameter	Value
β_p	0.05
β_d	2.5
$C_{\varepsilon 4}$	10
C_{PB}	5

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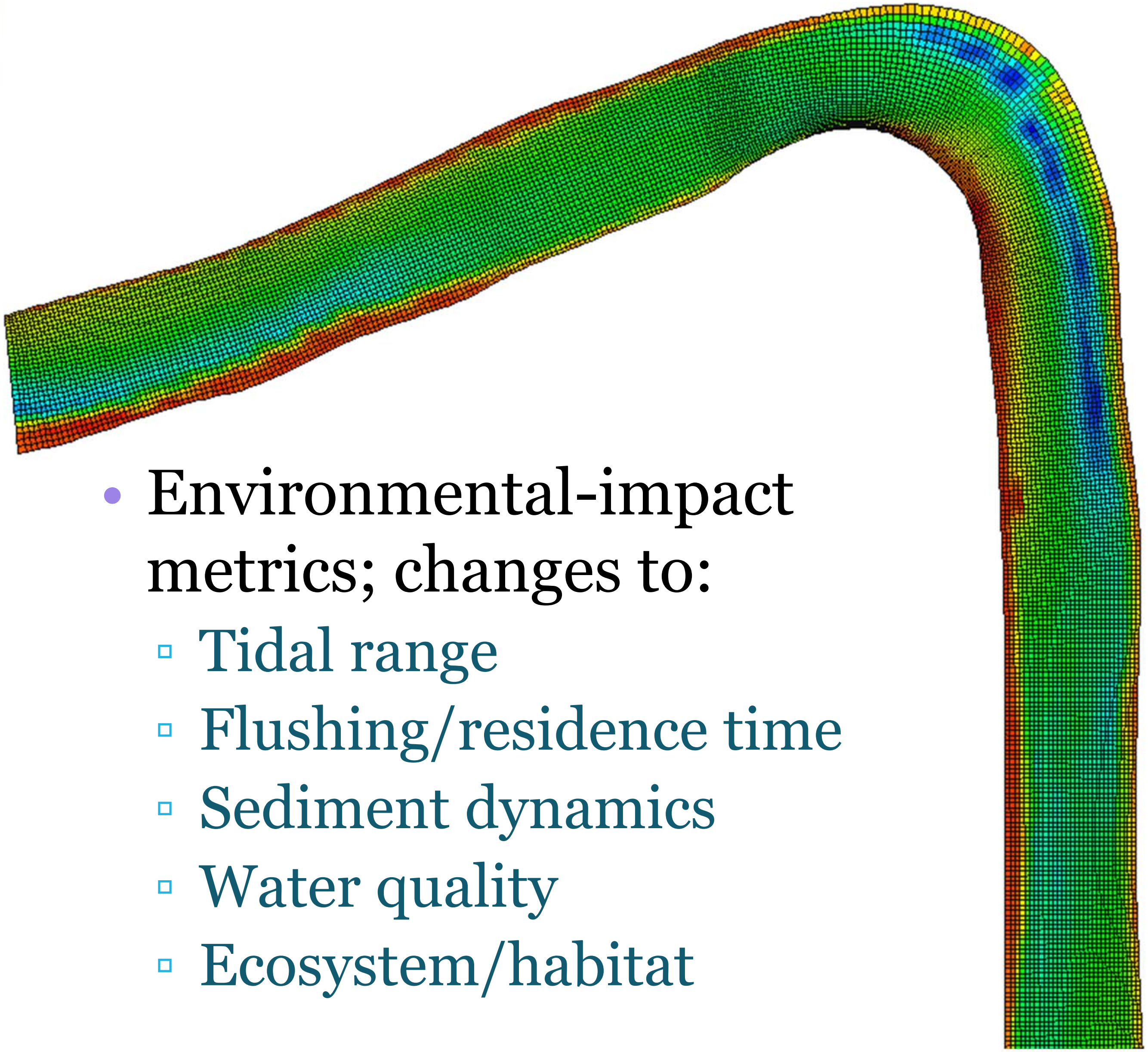
Future Studies



- Environmental-impact metrics; changes to:
  - Tidal range
  - Flushing/residence time
  - Sediment dynamics
  - Water quality
  - Ecosystem/habitat

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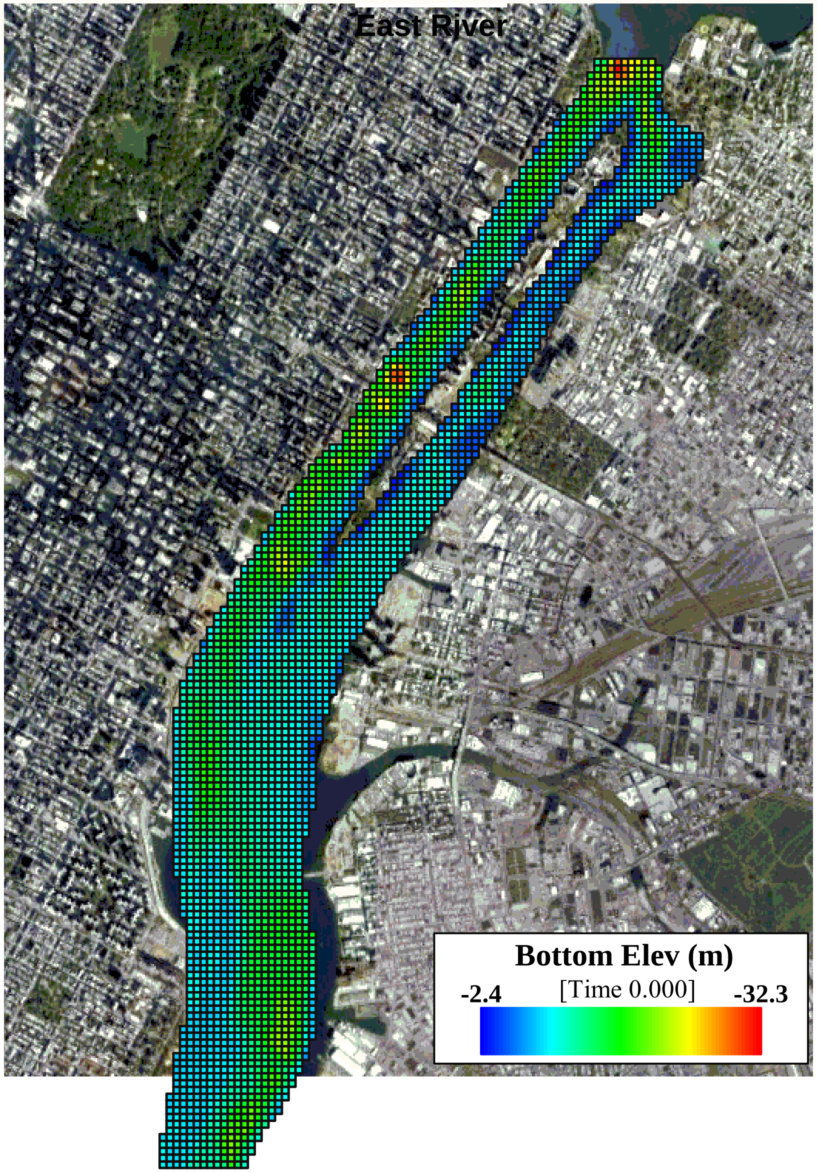
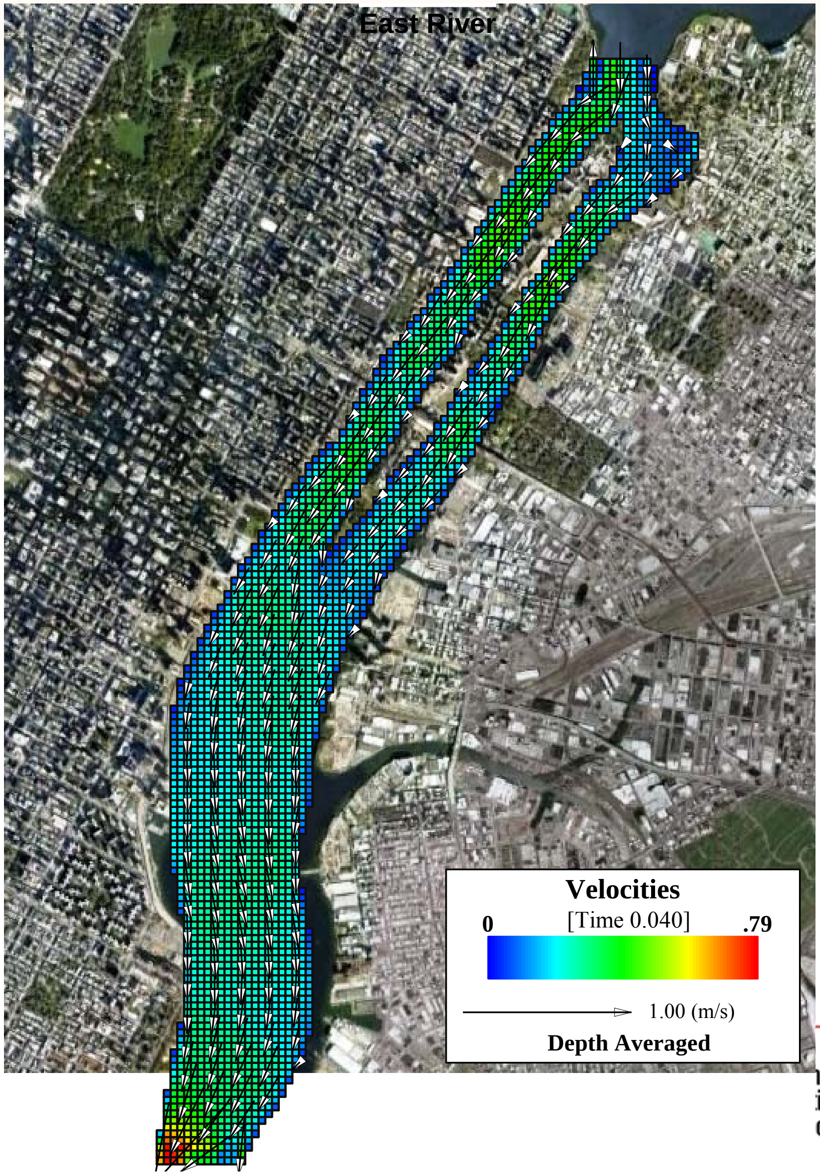
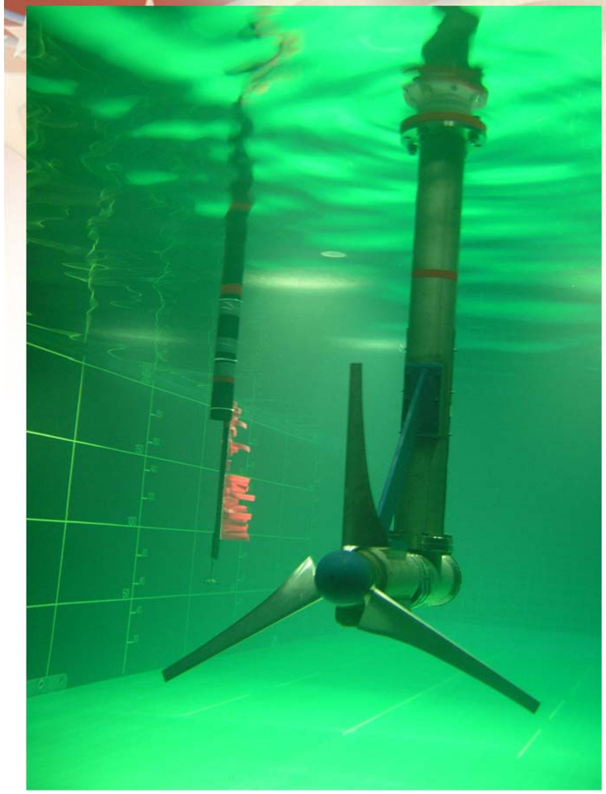
East River Model

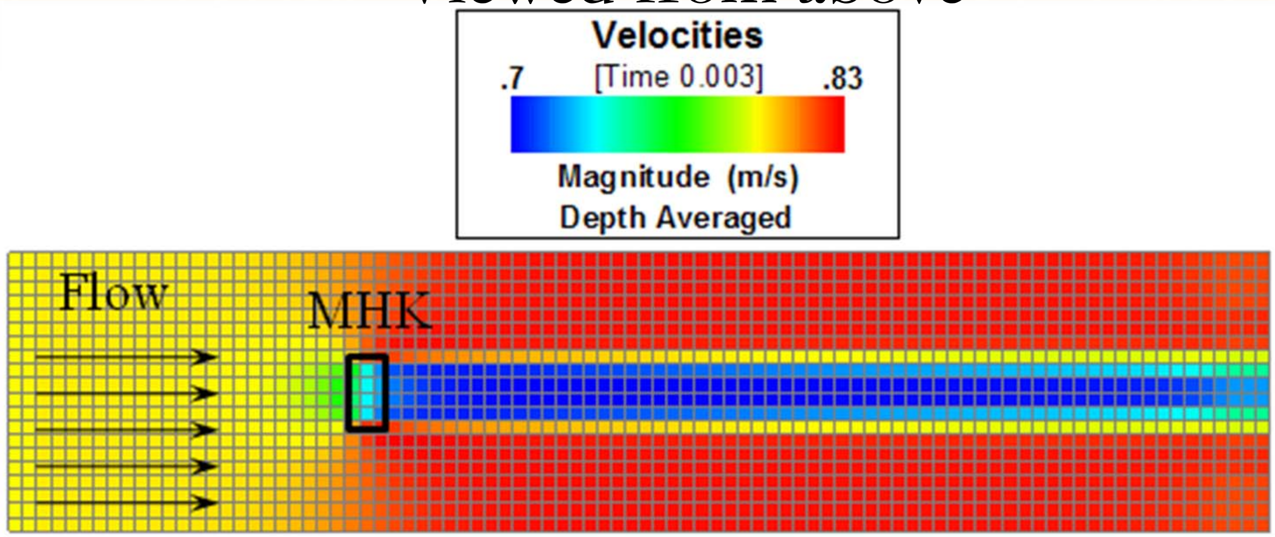


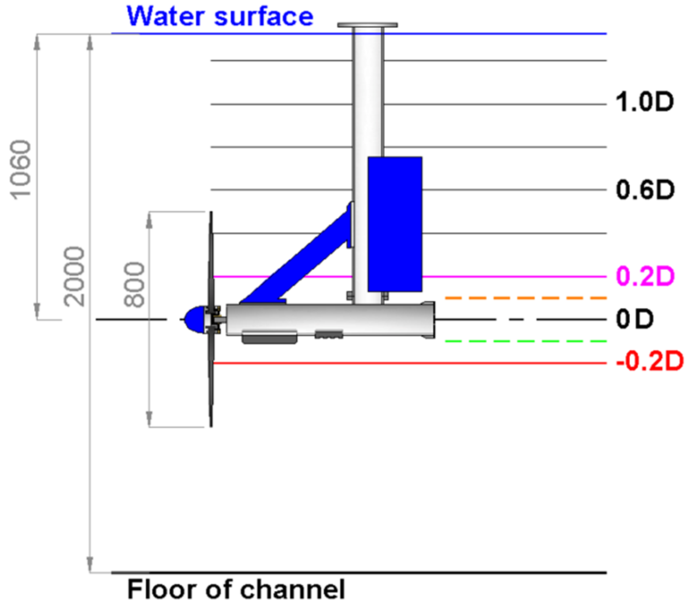




Model Verification

Viewed from above





Parameter	Value
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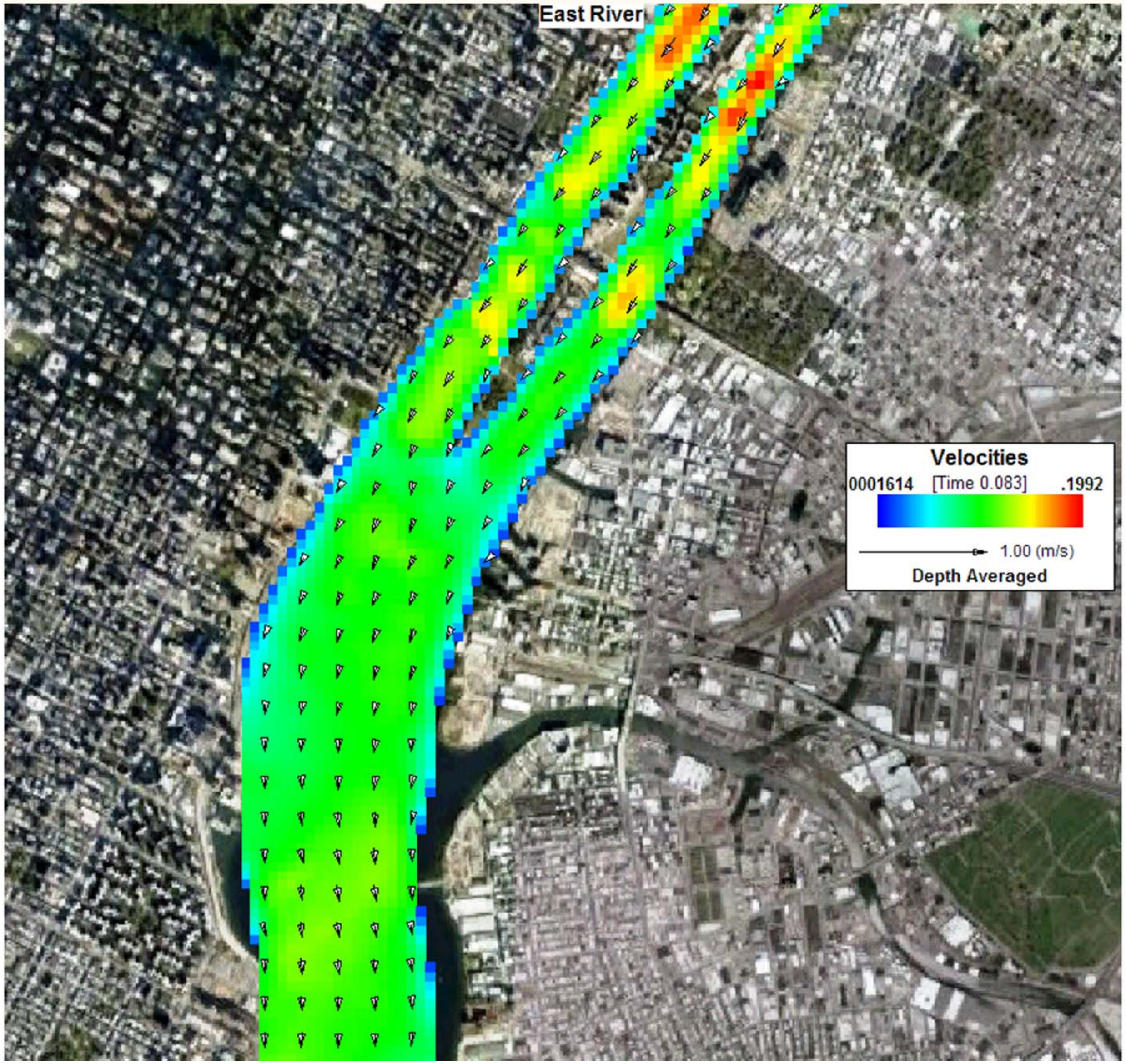
East River Model

DS-INTL

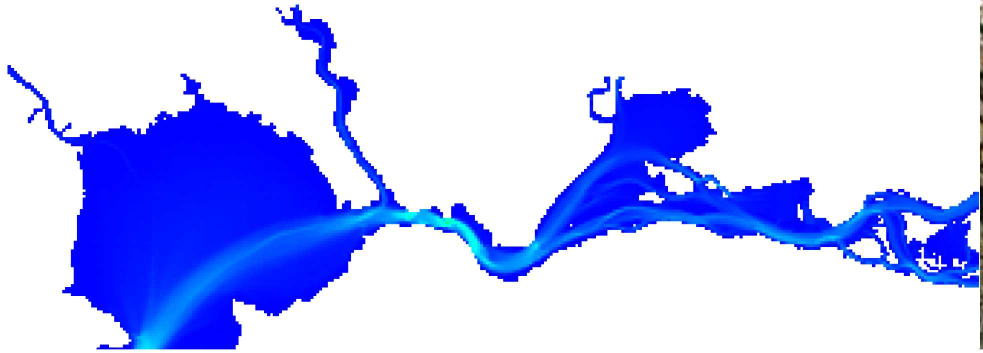
DS-INTL

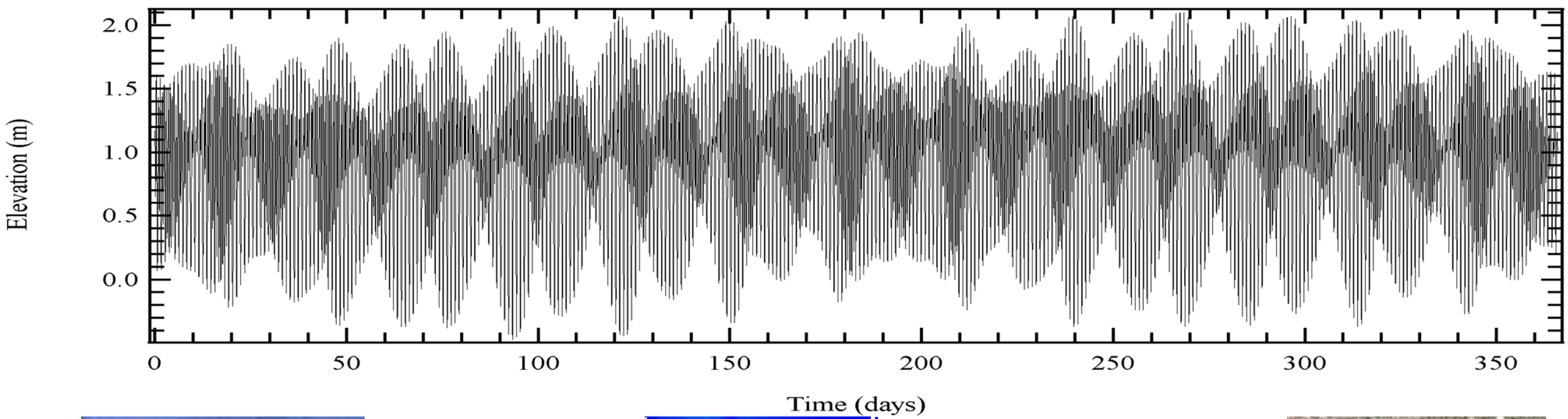


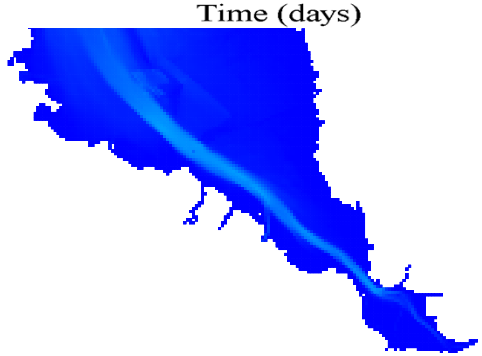
DS-INTL

DS-INTL

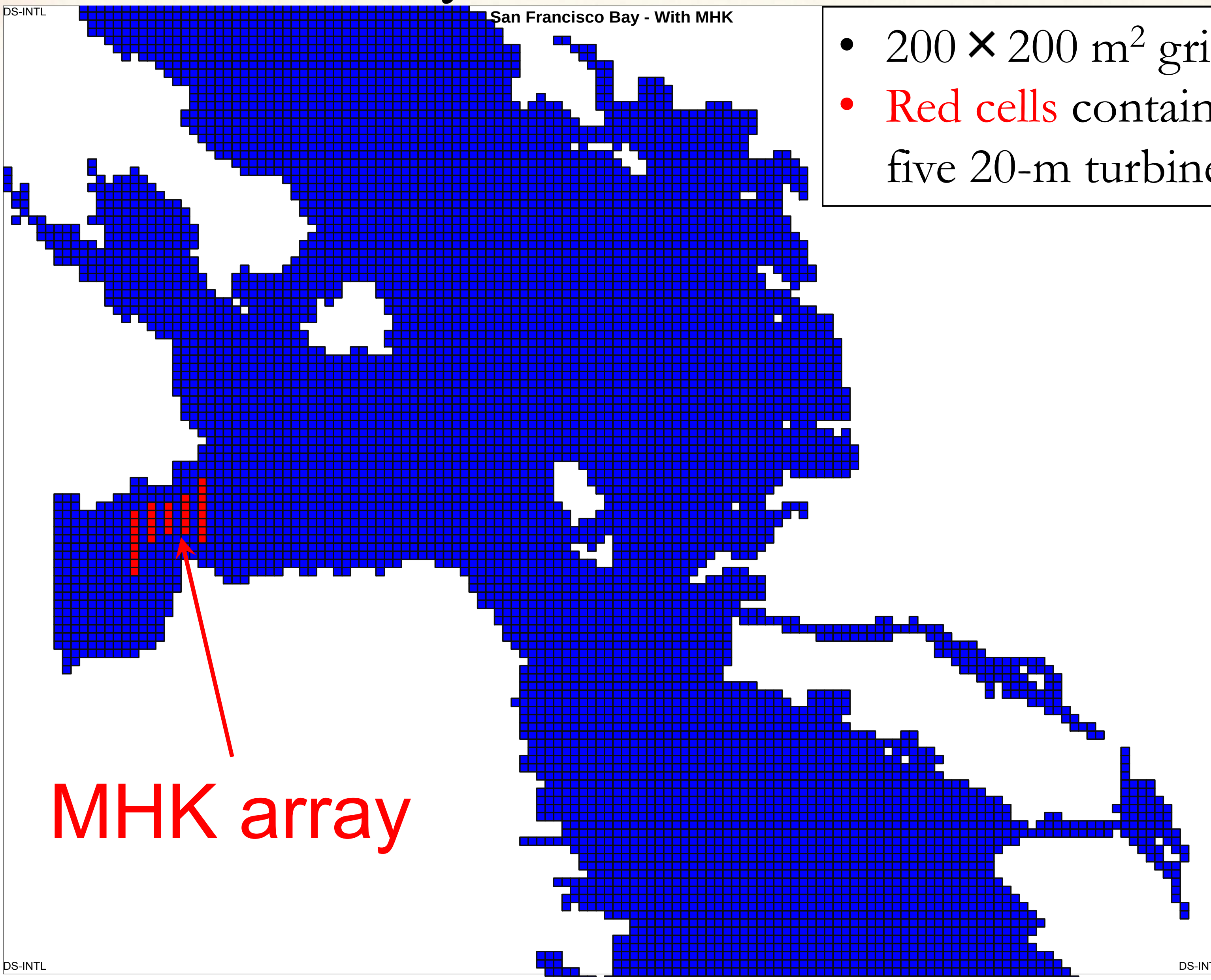
San Francisco Bay Model





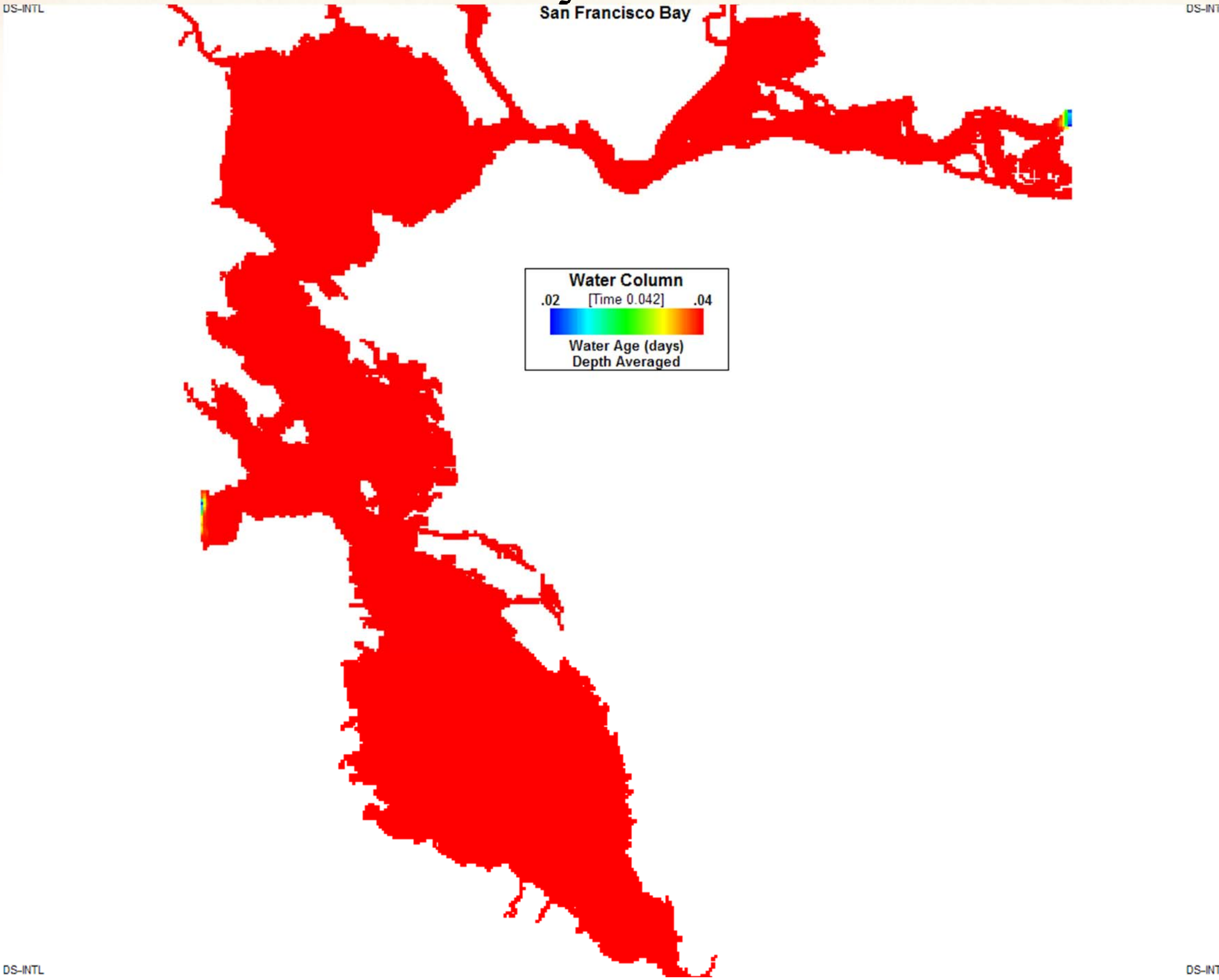


MHK Array



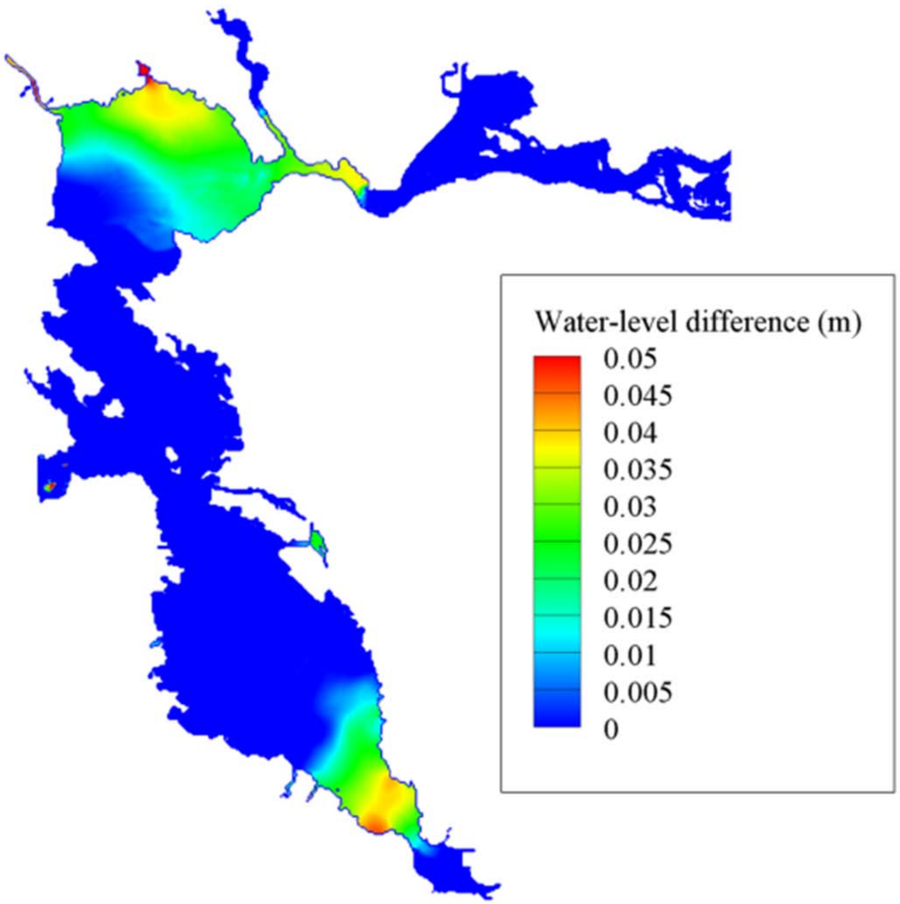
- 200 × 200 m^2 grid cells
- Red cells contain: five 20-m turbines

San Francisco Bay Model – Water Age

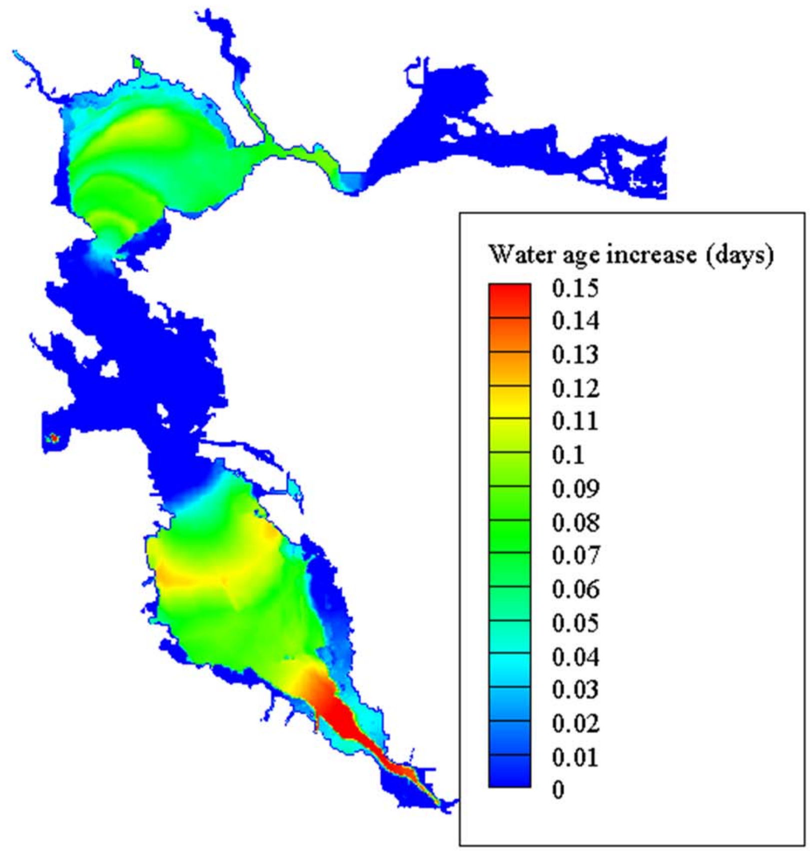


Changes (Tidal Range and Water Age)

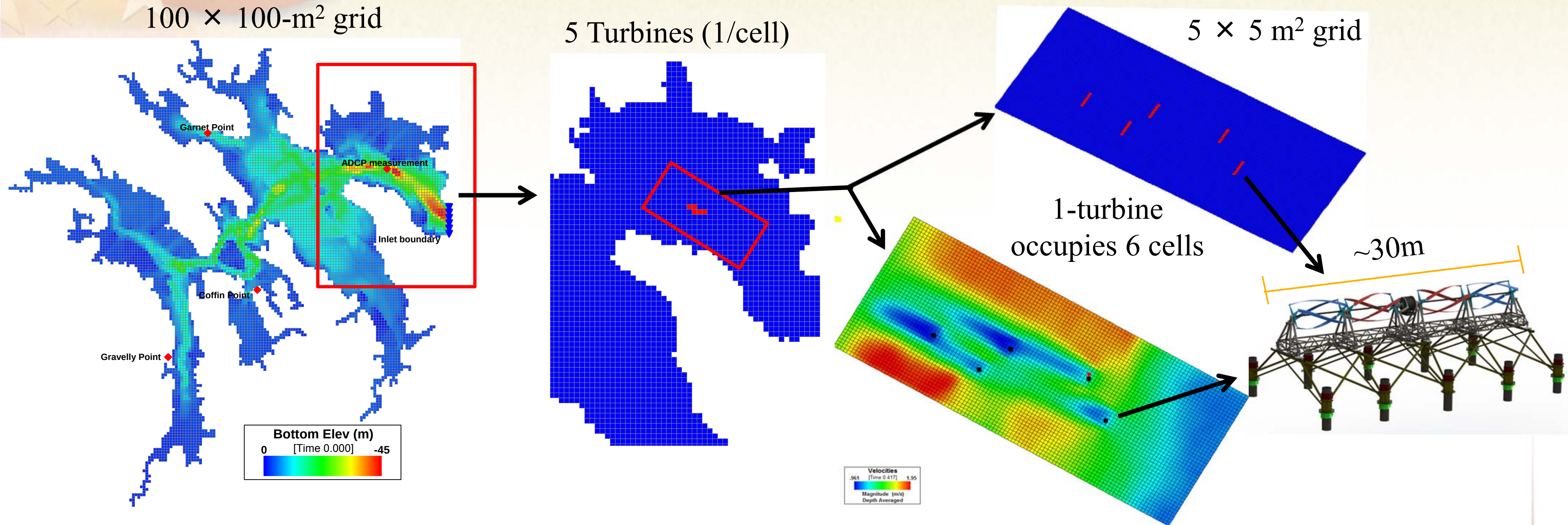
Tidal amplitude



Water age (after 30 days)

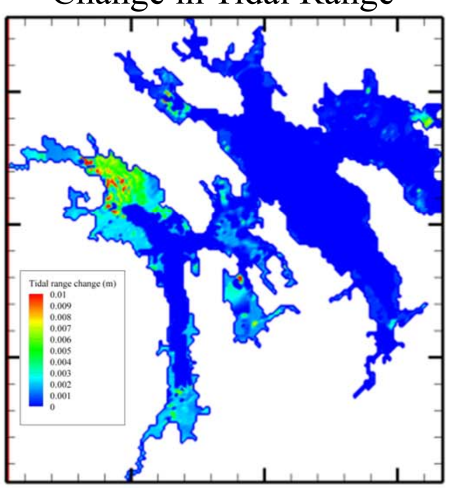


Cobscook Bay Model - Demonstration

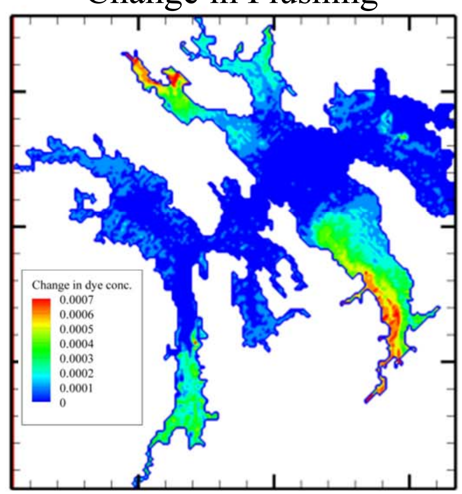


Effects of 5 Turbines is Negligible

Change in Tidal Range

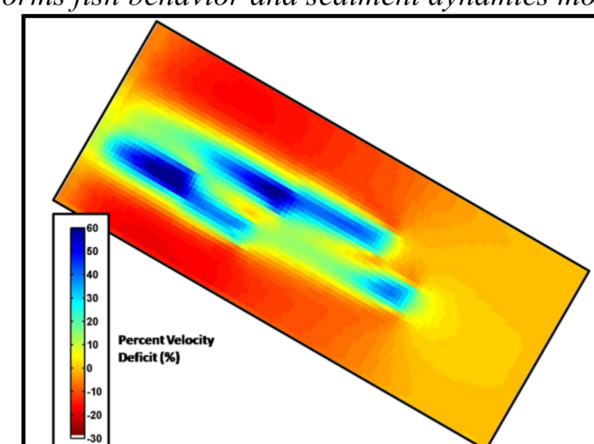


Change in Flushing



Velocity Change Map (without – with turbines)

Informs fish behavior and sediment dynamics modeling



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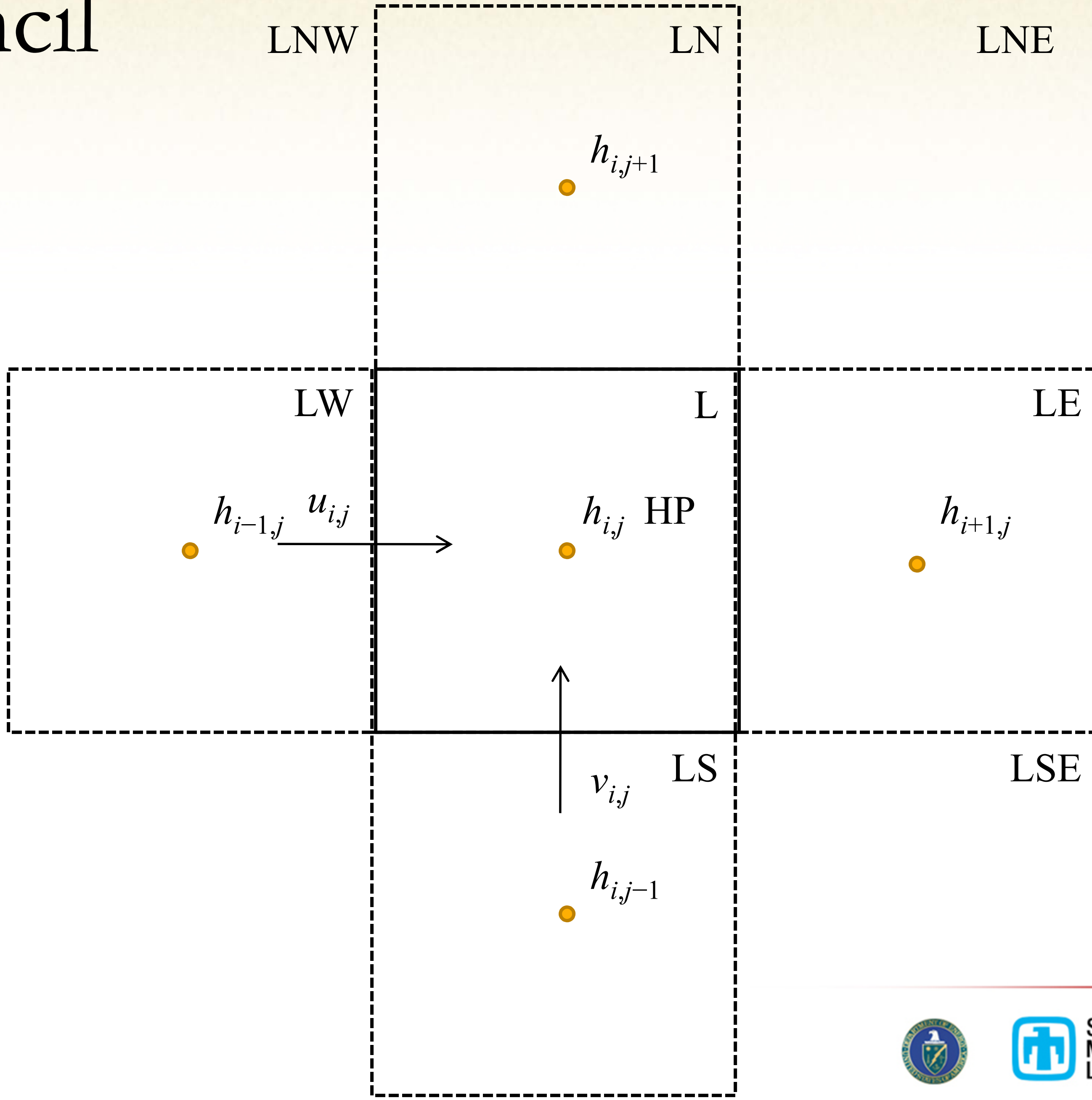
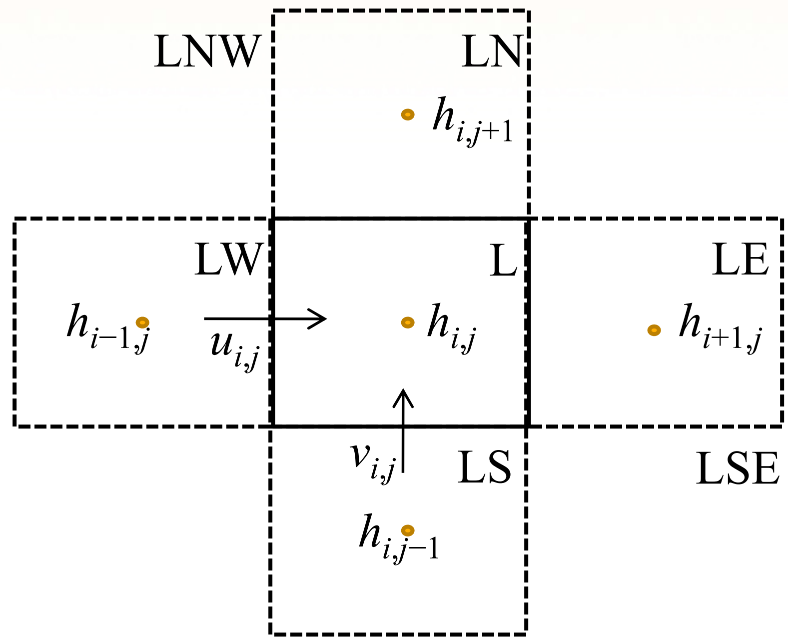
Model Specifics

FD Stencil

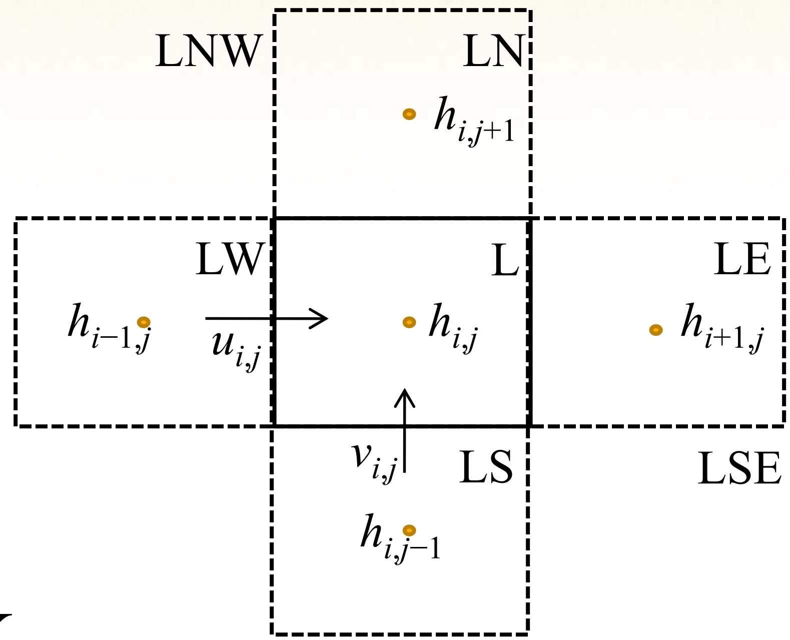


Velocity Stencil



- Cell-centered velocities:
  $u = ½(u_{L} + u_{LE})$
  $v = ½(v_{L} + v_{LN})$
- Face speeds:
  $u = \sqrt{[¼(u_{L} + u_{LE} + u_{LS} + u_{LSE})^2 + v_{L}^2]}$ (south)
  $v = \sqrt{[u_{L}^2 + ¼(v_{L} + v_{LW} + v_{LN} + v_{LNW})^2]}$ (west)

Forces from MHK Devices



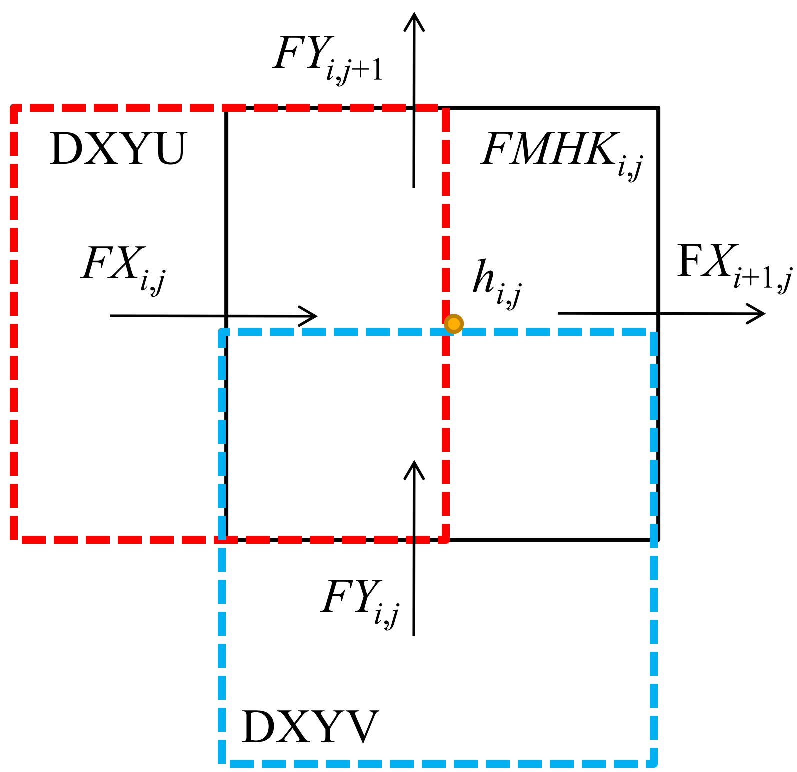
- Forces are applied at faces (not cell centers)
- Cell-centered force from MHK are distributed across both faces of the cell by area weight
- Force is measured in units of m^4/s^2 (multiply this by density later to get Newtons)
- Power per unit density is: $P_{\mathrm{MHK}} = \frac{1}{2} C_{\mathrm{T}} A_{\mathrm{MHK}} |q| q^2$ (m^5/s^2)

Internal/External Solutions

- There are internal- and external-mode solutions in EFDC; the internal mode is layer-based and the external is (water) column-based
- Sum of forces on internal mode is zero, but unequal forces (shear, MHK, vegetation, etc.) are applied to each layer to "rearrange" the flow
- MHK forces will act on the water column as a whole through the external mode solution

Force on a Cell Face

- Face-centered areas used for force calculations:
  Area for U-face = DXYU
  Area for V-face = DXYV

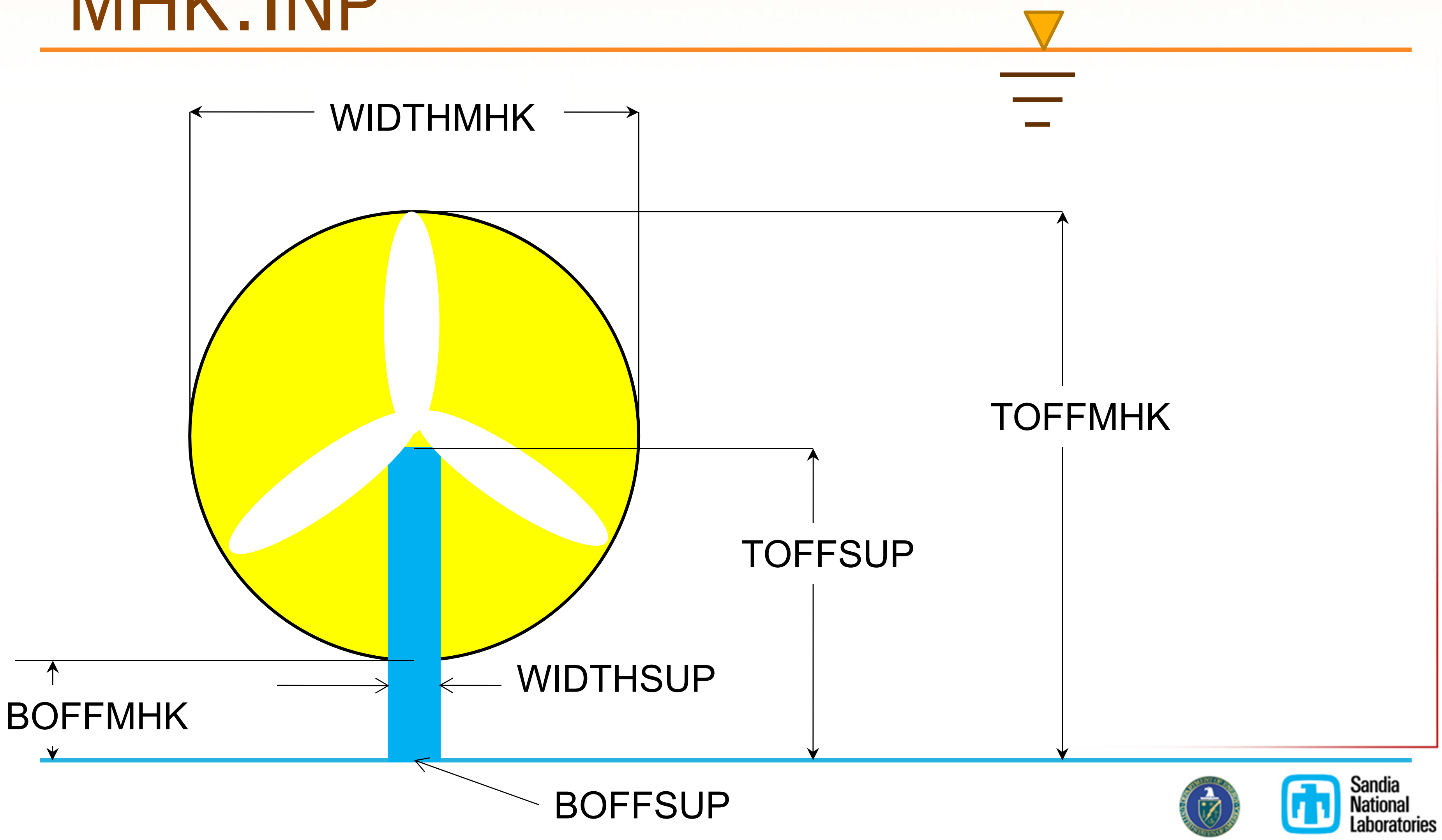


MHK.INP

C WIDTHMHK is the width of MHK device type
C WIDTHSUP is the width of MHK support structure type
C BOFFMHK is the bottom offset of the MHK device type (how far from the bottom)
C BOFFSUP is the bottom offset of the MHK support structure type
C TOFFMHK is the top offset of the MHK device type
C TOFFSUP is the top offset of the MHK support structure type
C CTMHK is the thrust coefficient of MHK device type
C CDSUP is the coefficient of power dissipation of MHK support structure type
C VMINCUT is the minimum velocity cut-in for MHK device type power curve
C VMAXCUT is the maximum velocity cut-out for MHK device type power curve
C DENMHK is the number of MHK devices in a cell

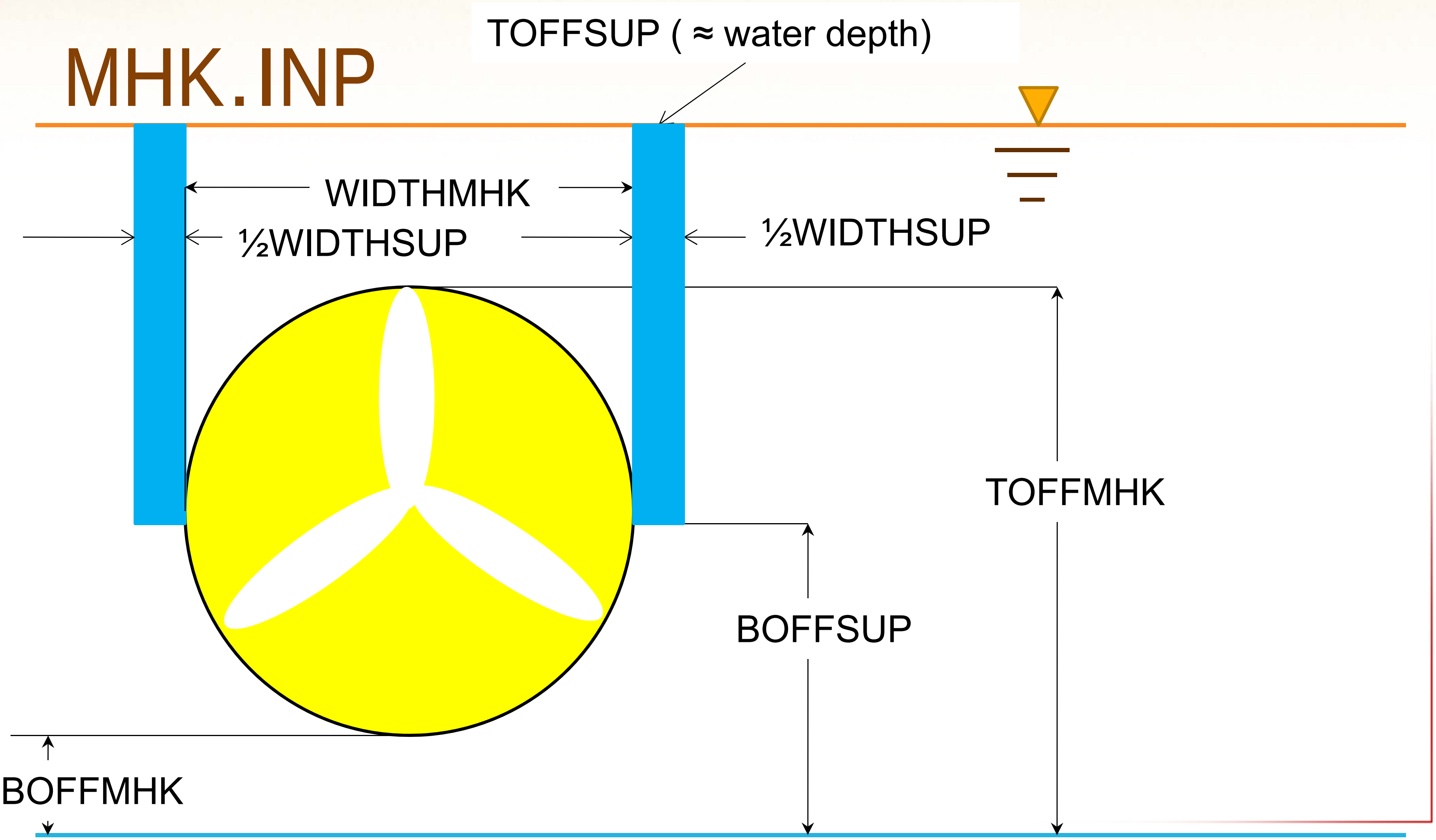
Bottom Mounted

MHK.INP



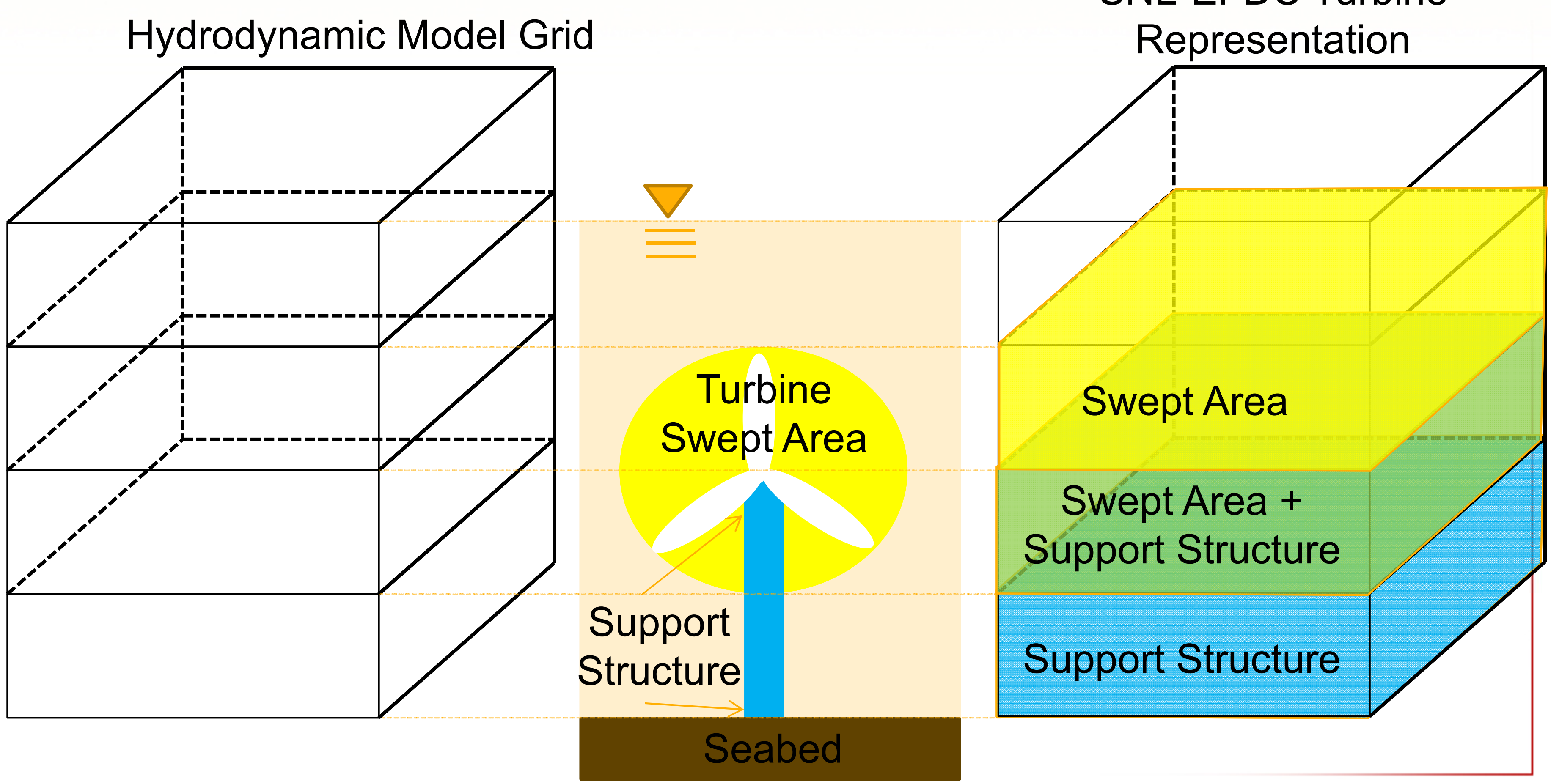
Top Mounted

MHK.INP



MHK-Module Porous Approximation

- MHK can be represented with multiple cells or contained within a single cell
- MHK can occupy an entire cell or a fraction of a cell



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