SAND2011-2350C

SNL MHK Modeling Activities

Partners:

•**Labs:** NREL, PNNL, ORNL

•**Universities:** Penn State ARL, OSU, UC Davis, UW, Bucknell, UMN

•**Industry:** Re Vision, SEA Engineering, Columbia Power Technology, Verdant, Berkeley Wave Tank

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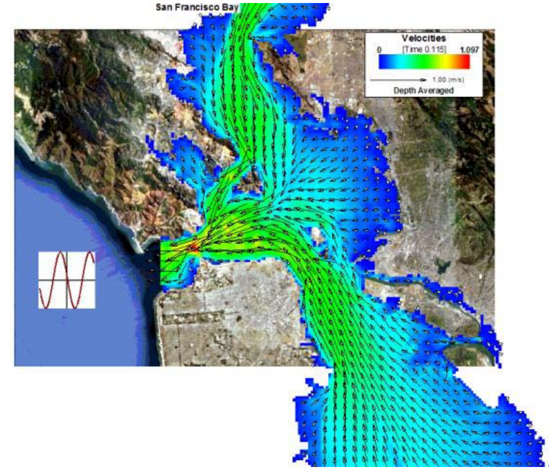
Key Objectives and Approach

Use analytical tools, computer models, and testing to investigate:

- Component and system performance (small scale)
- What happens when energy is extracted from a system (large scale)



Outcome

1. Reduce costs for MHK build out with predicative simulations
2. Understanding environmental limits to MHK development
3. Provide MHK specific data sets and assessment tools

Optimize for maximum energy capture with minimum environmental impact

MHK Technology Development Task Structure*

1.3.1 WEC Systems	1.3.2 Current/Tidal Systems
WEC Device Modeling	Single Turbine Performance Modeling
WEC Arrays	Array Performance Modeling
Wave Environment Hydrology	Large Scale Hydrology Modeling for Inflow
	Turbine Design

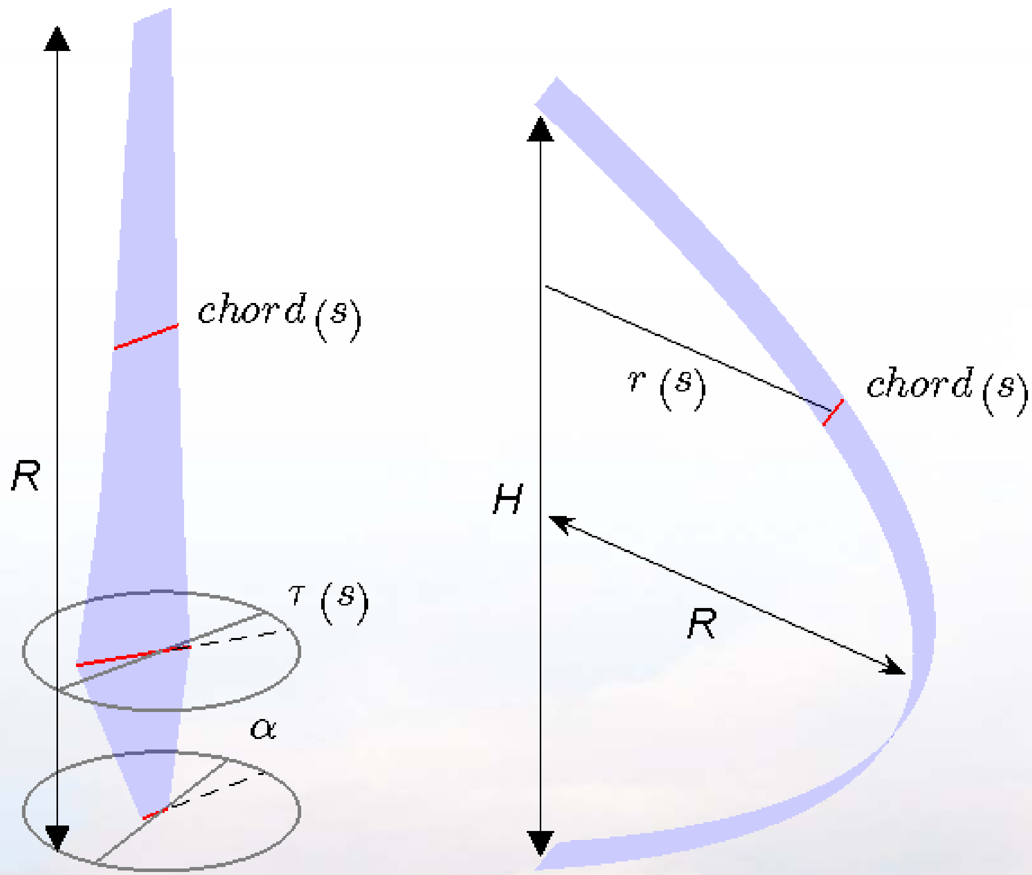
*SNL is also the lead for modeling and testing activities in Reference Model (1.2.5), Market Acceleration (2.1.X) and 1.4.1 Testing and Evaluation tasks

Single Turbine Performance Modeling

CACTUS (Code for Axial and Cross-flow TUrbine Simulation) Overview

- **Marine turbine performance simulation**
- **Potential flow representation of fluid dynamics**
  - Lifting-line element description of blade
  - Free vortex lattice description of wake
  - Panel elements used on boundaries (bottom and free surface)
- **VDART3 heritage**
  - SNL free vortex wake code for Darrieus wind turbines
- **Fortran 95 implementation**
  - Modular code structure

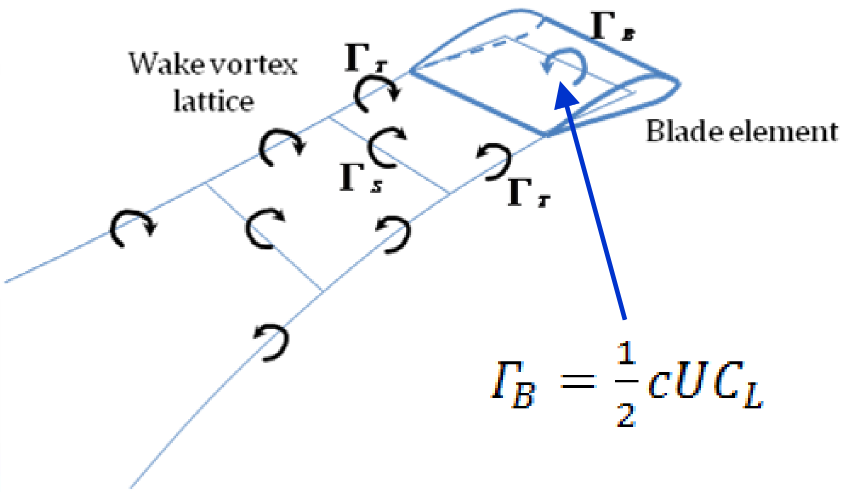
Rotor Geometry



a) Axial turbine blade b) Cross-flow turbine blade

- Can model both axial and cross-flow rotors
- General user-specified geometry interface is planned

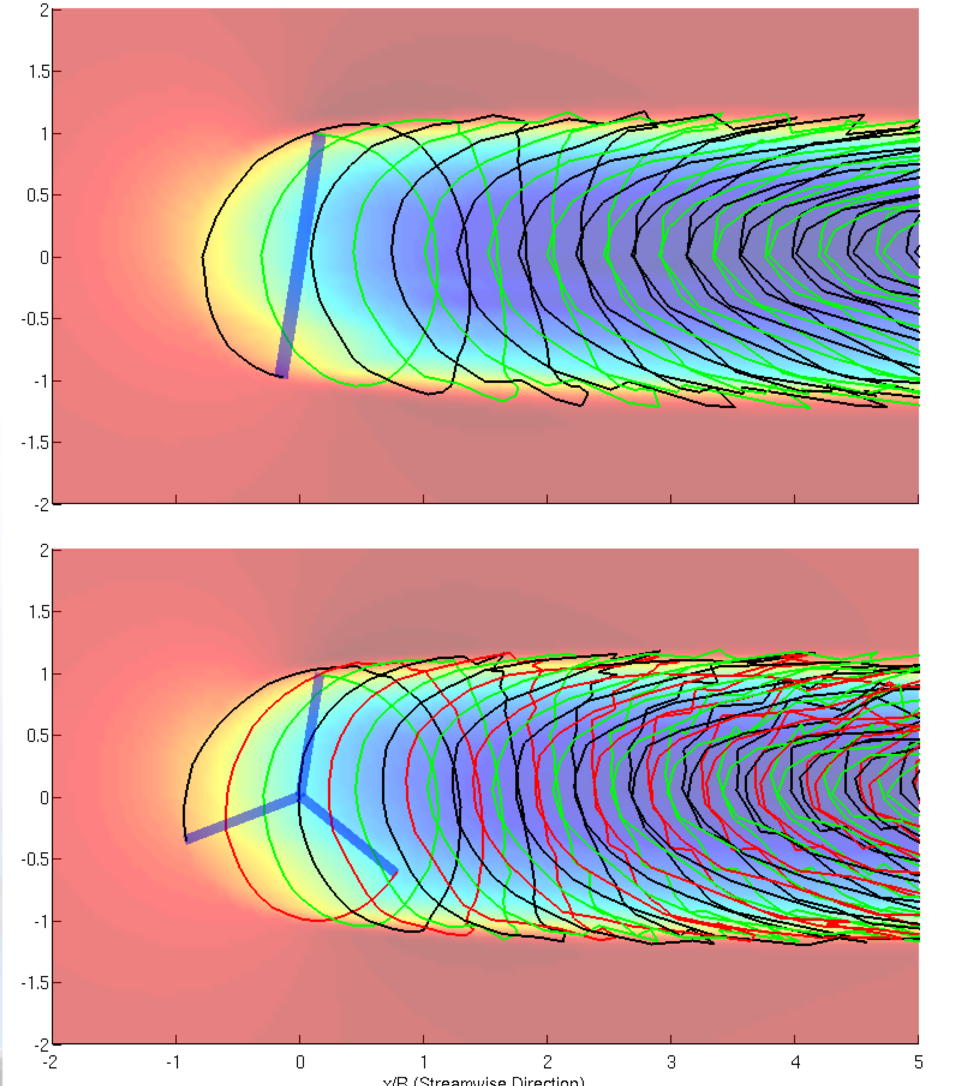
Blade Element Method



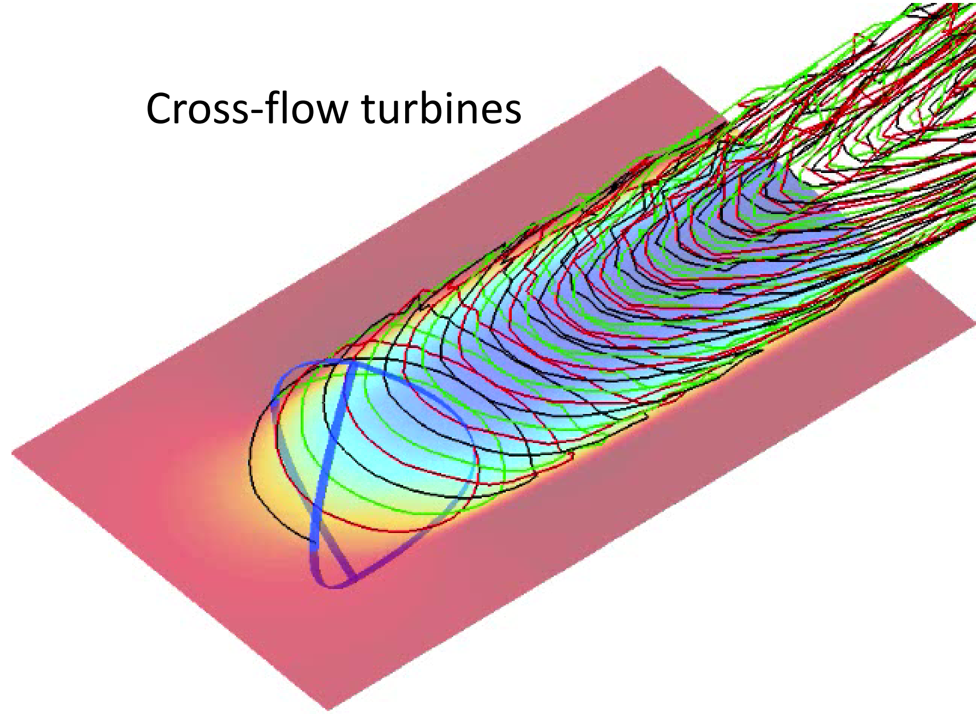
- **Blade loads from empirical data**
  - Steady 2D airfoil data including non-linear effects
  - Attached flow dynamic effects from pitching flat plate theory
  - Additional models for dynamic stall effects
- **Blades represented as lifting lines**
  - Bound vorticity on each element given by Kutta-Joukowski theorem
  - Spanwise variation in bound vorticity creates trailing wake vorticity
  - Temporal variation in bound vorticity creates spanwise wake vorticity
- **Bound and wake vorticity model effects of rotor on fluid flow**

MATLAB Post Processing

Axial-flow turbines



Cross-flow turbines



- **Visualizations of velocity field and vortex filament traces.**

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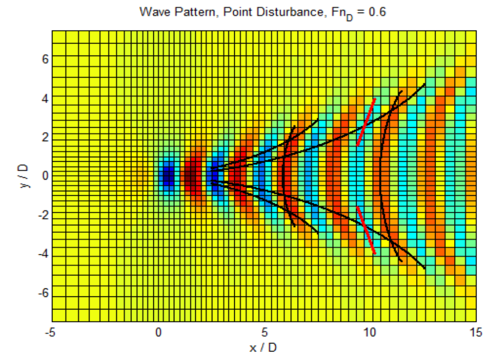
Progress and Future Enhancements

- **Progress**
  - **Free Surface Verification**
  - **Validation with Sandia 34 Meter VAWT**
- **Future Activities**
  - **Cavitation onset prediction**
    - Significant damage is possible for blades operating in cavitating flow
    - Onset when fluid pressure reaches vapor pressure
  - **Panel element blades**
    - Full description of blade geometry and near field flow
    - May be necessary for high solidity rotors
  - **Acceleration of wake influence calculations**
    - Wake velocity influence calculation is very expensive
    - Parallel implementation on GPU
    - Calculation easily ported using CUDA programming language



Array Performance Modeling

Updated EFDC Model

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SNL-EFDC

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Remains Public Domain

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Turbine Energy Extraction

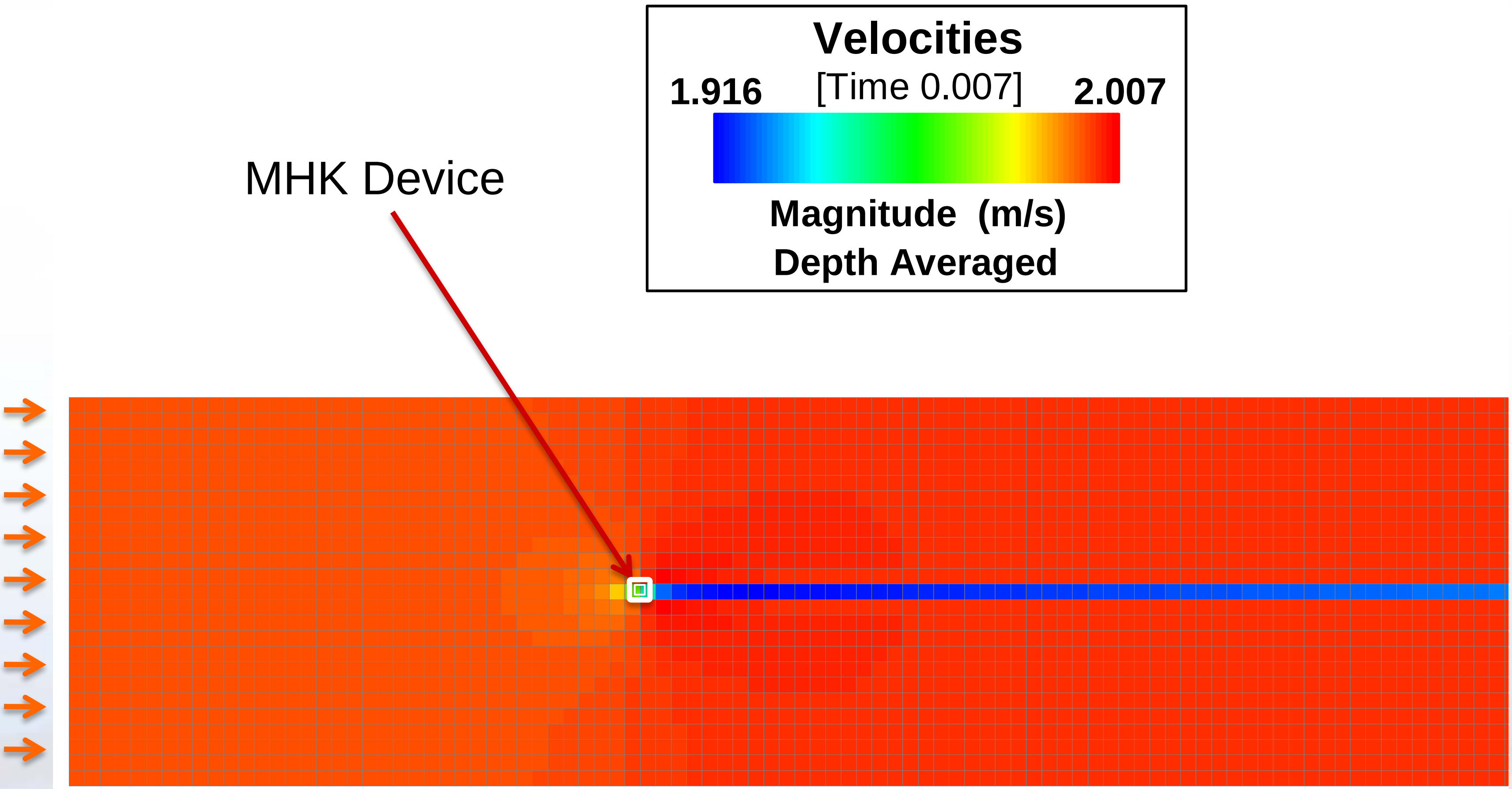
- Turbine energy extraction is manifest as:
  - Decreased momentum
  - Altered (usually increased) turbulent kinetic energy
  - Increased turbulence dissipation rate (turbulent length scale)
- These quantities (momentum and *K-ε) are advected* and *dispersed* downstream

Momentum Sink: Turbine

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

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

Single Turbine Model – Momentum Sink Only



- Overly persistent velocity defect

$K-\varepsilon$ Modifications: Turbine

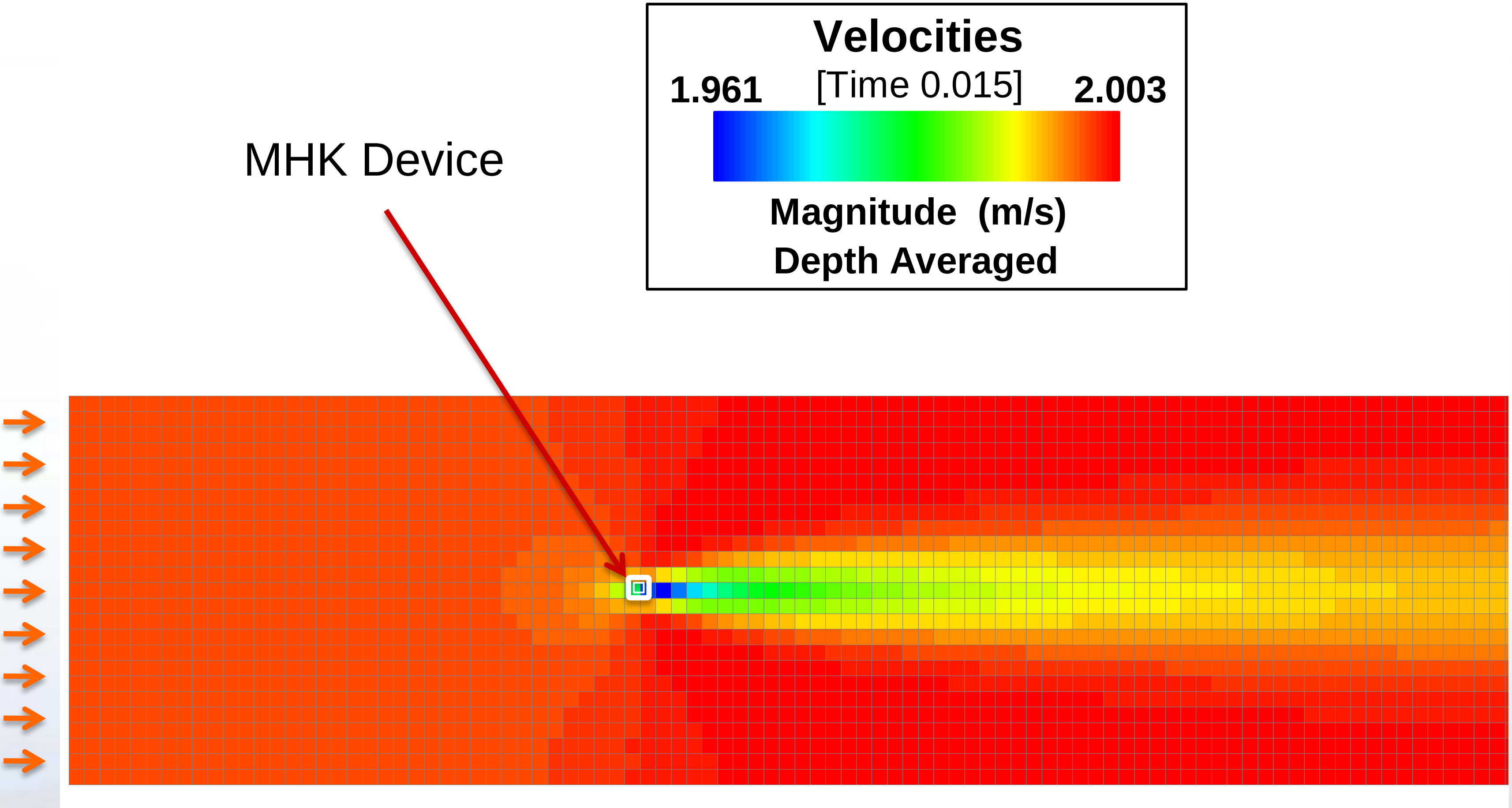
Empirical constants

$$S_K = \frac{1}{2} C_T A_{MHK} \left(\beta_p U^3 - \beta_d U K \right)$$

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

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*.

Single Turbine Model – K–e Sinks Included



- Realistic fluid energy loss/wake behavior
- Verified with Meyer and Bahaj, 2010

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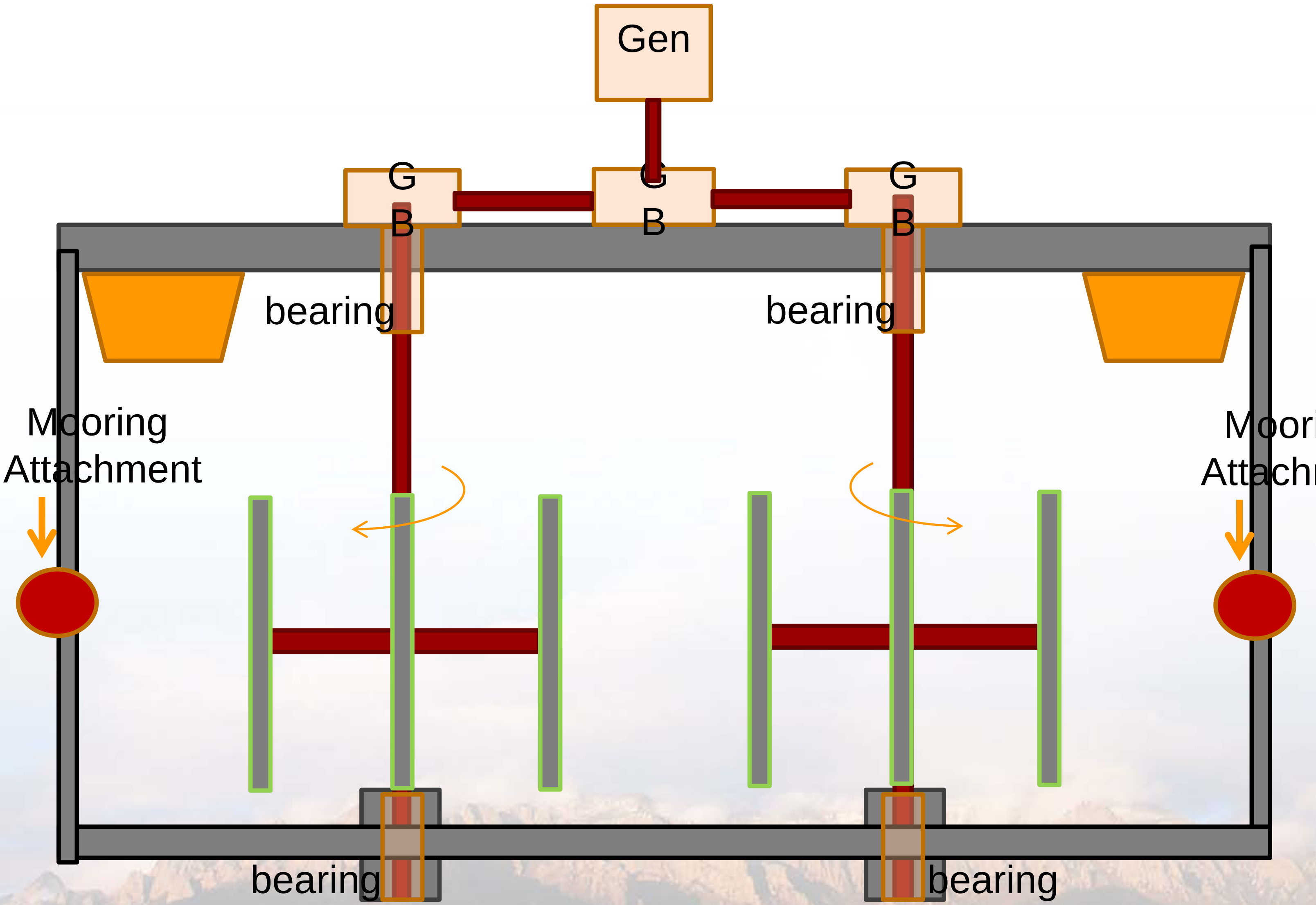
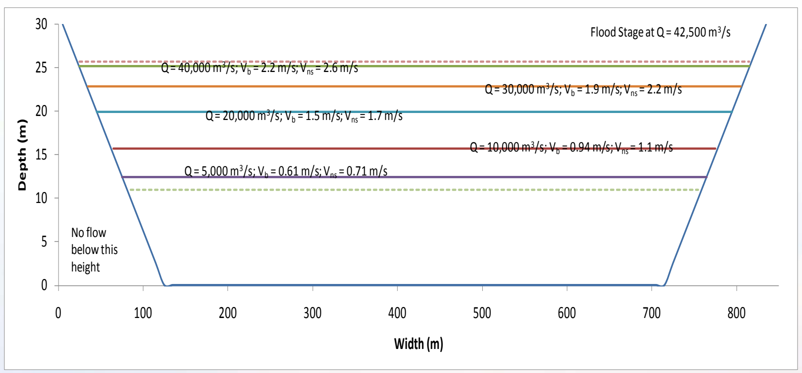
Floating Platform with Duel Rotors

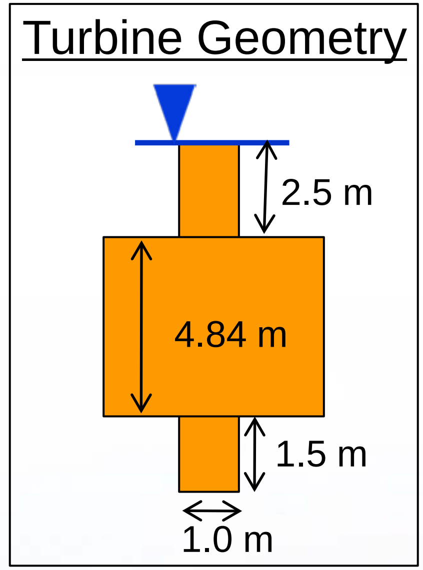


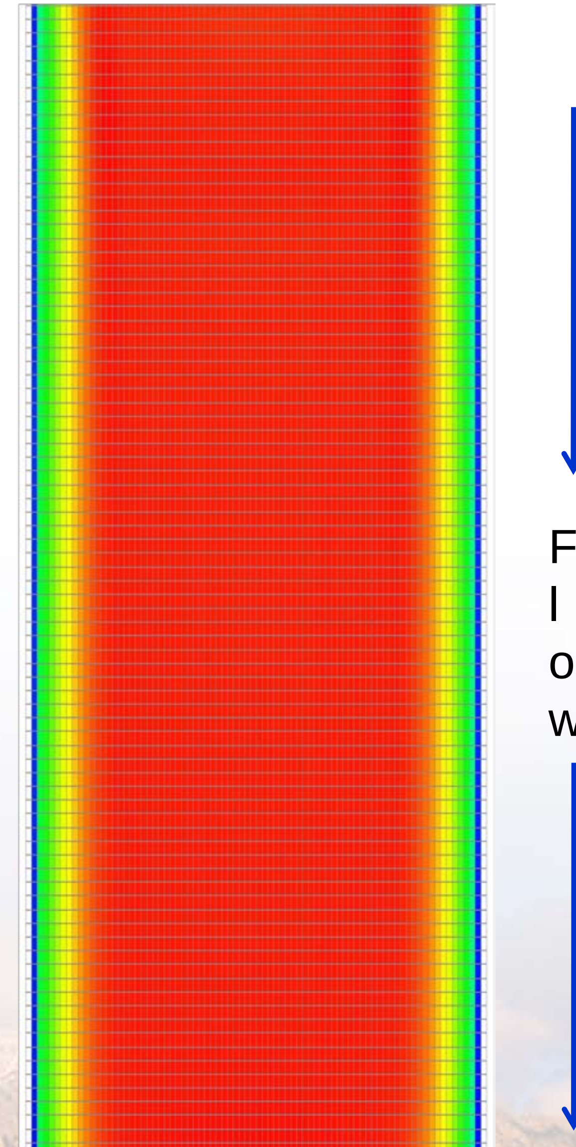
Model Domain: Turbine Array Optimization

General Model Conditions

- Grid is 840 m by 4,200 m
- Cells are 10 m x 30 m
- 10 vertical layers
- Channel full top width is 840 m
- Bottom width is 600 m
- Max depth is 30 m



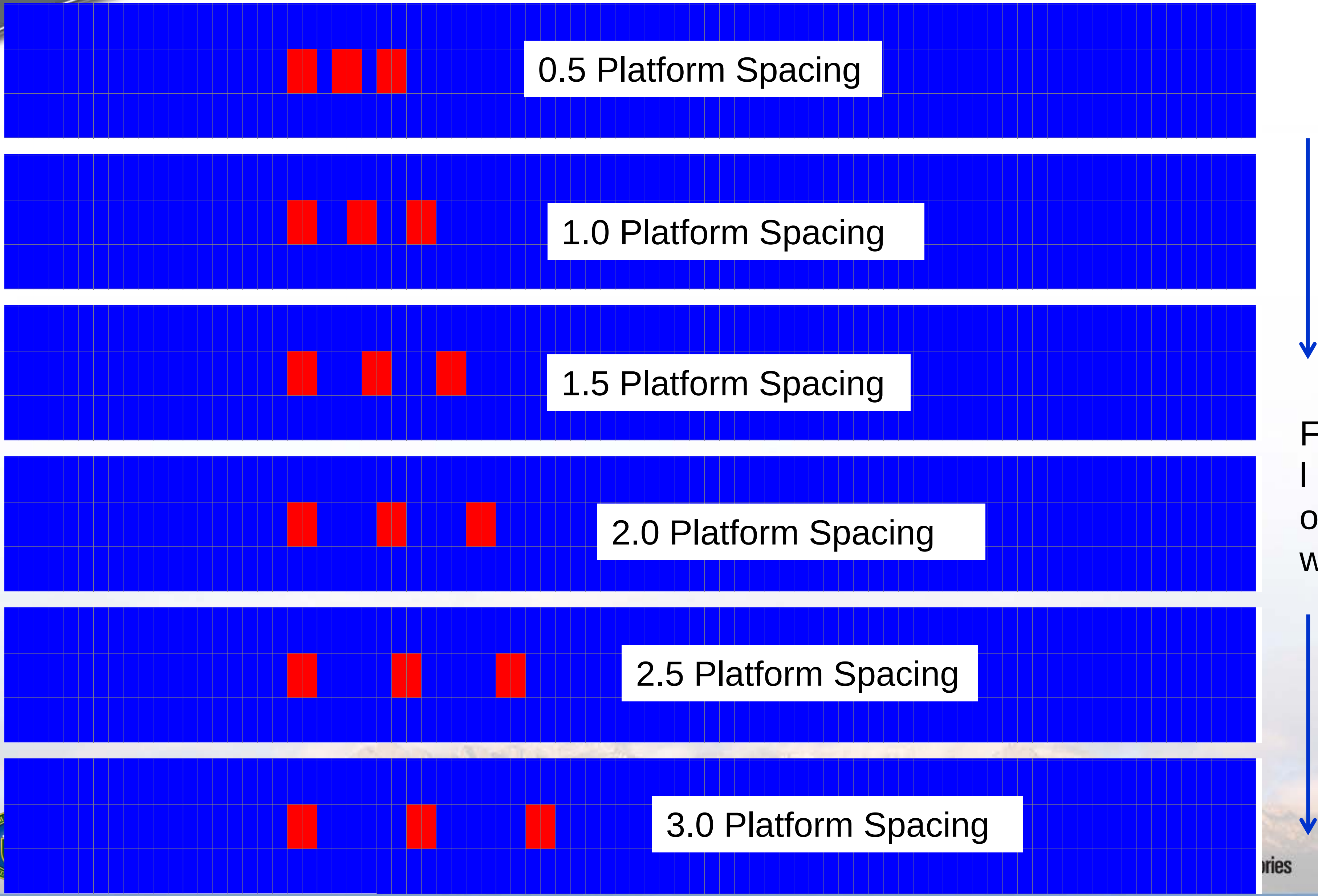




Specific Model Conditions

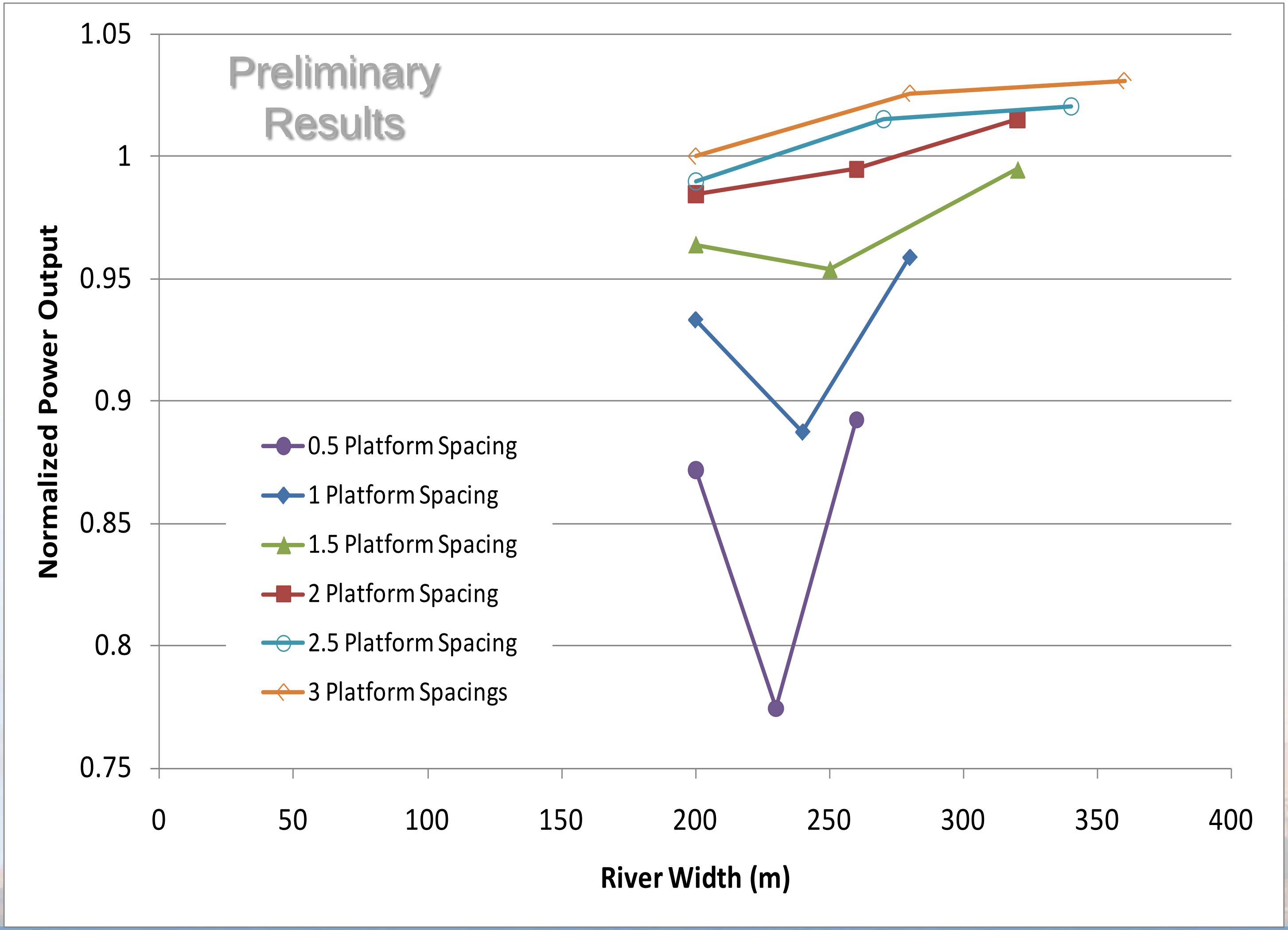
- Flow is constant 20,000 m^3/s
- $U_\infty \approx 1.6$ m/s
- Top width is ≈ 750 m
- Max depth is ≈ 20 m

Horizontal Turbine Array Optimization



Effects of Horizontal Turbine Spacing

Normalized by power output from 1 Platform near center of channel

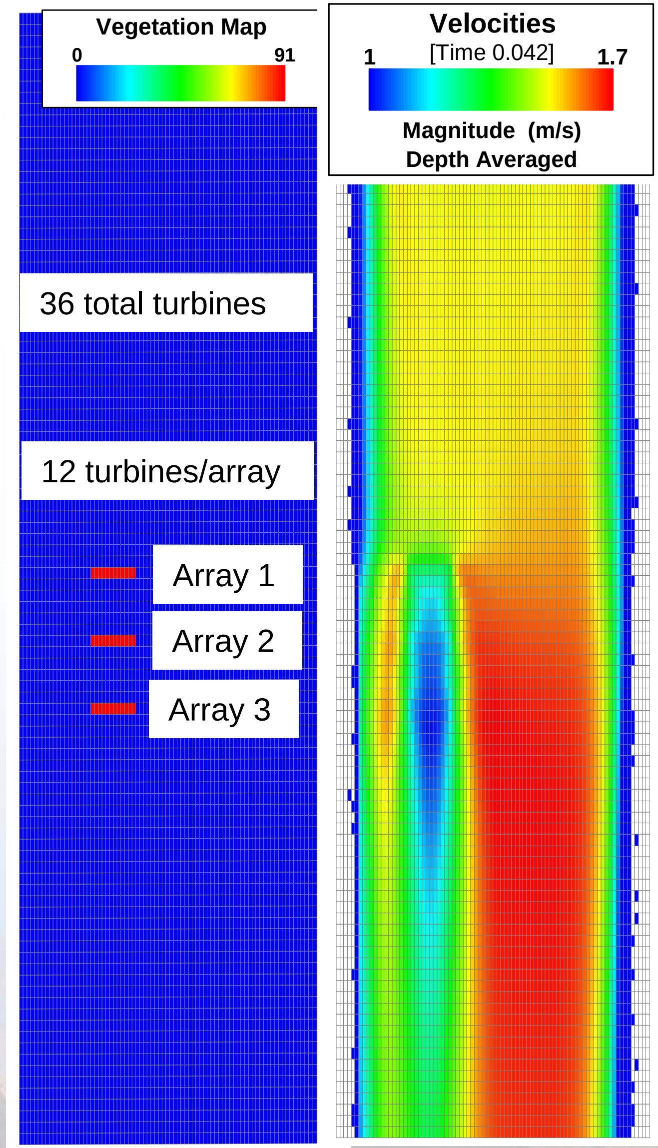


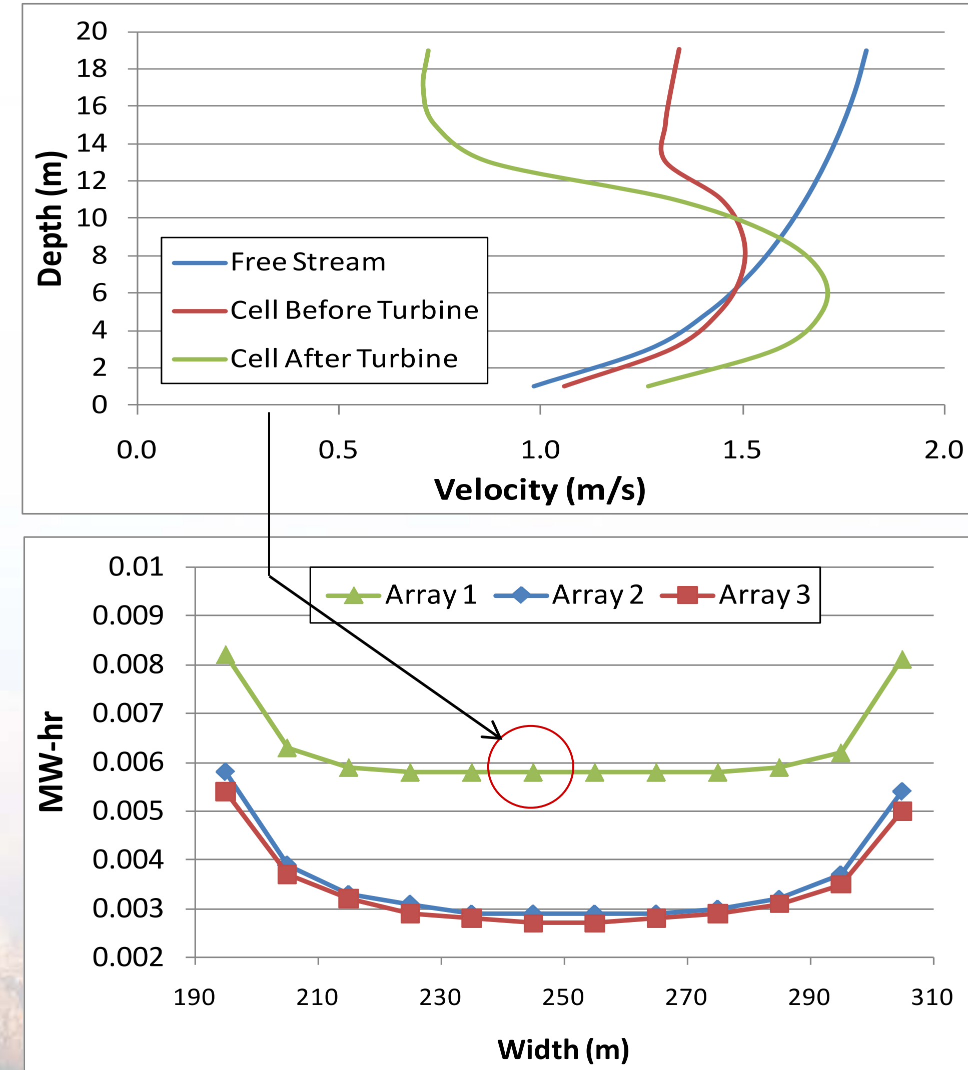
- The 'left' turbines are affected by horizontal velocity profile (slower flow nearer to bank).

- An increase in power (above a single platform by itself) can be seen as the turbines are placed further apart (helping each other).

Turbine Array Effects

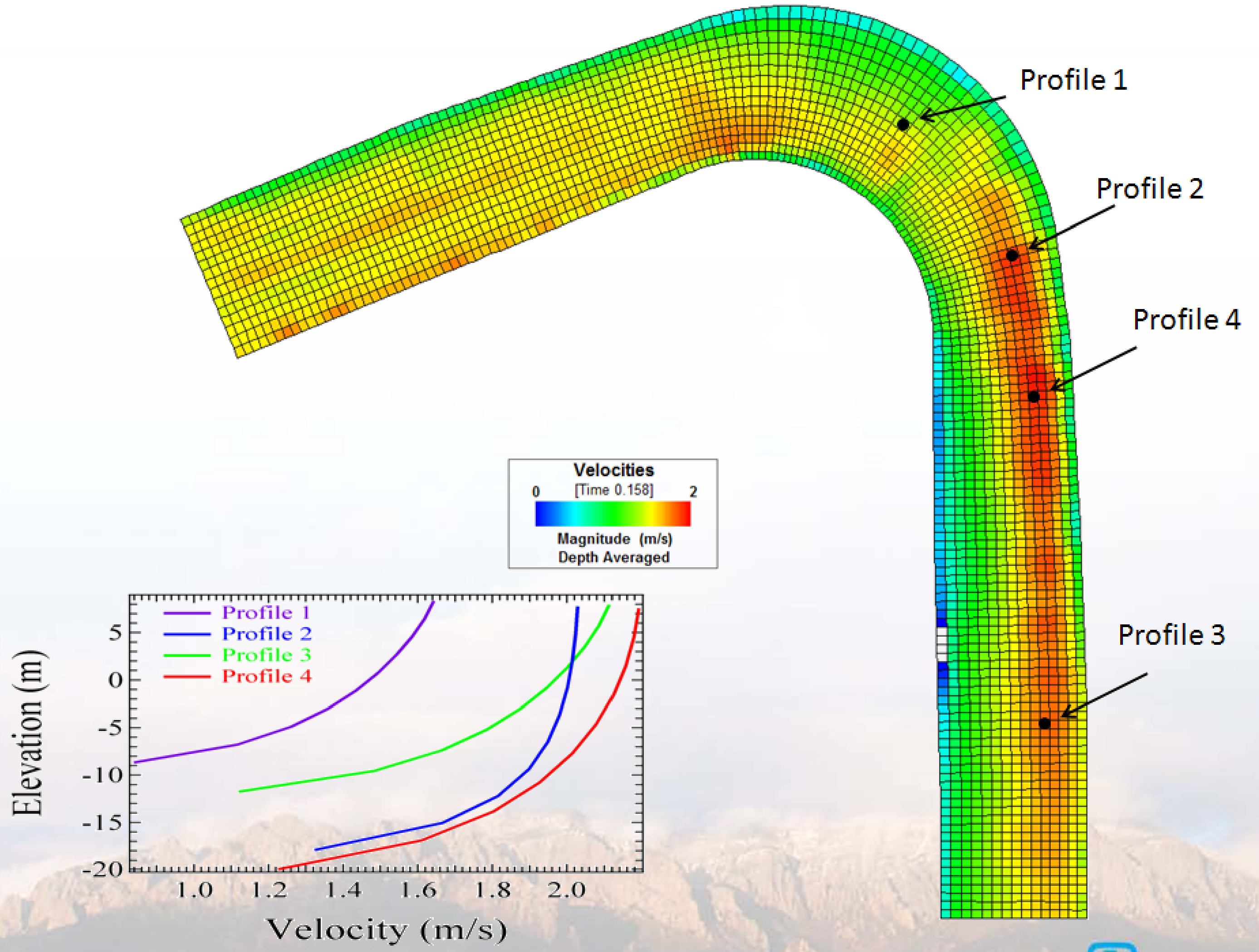
Preliminary Results





Large Scale Hydrology Modeling for Inflow

Mississippi River, Scotlandville Bend



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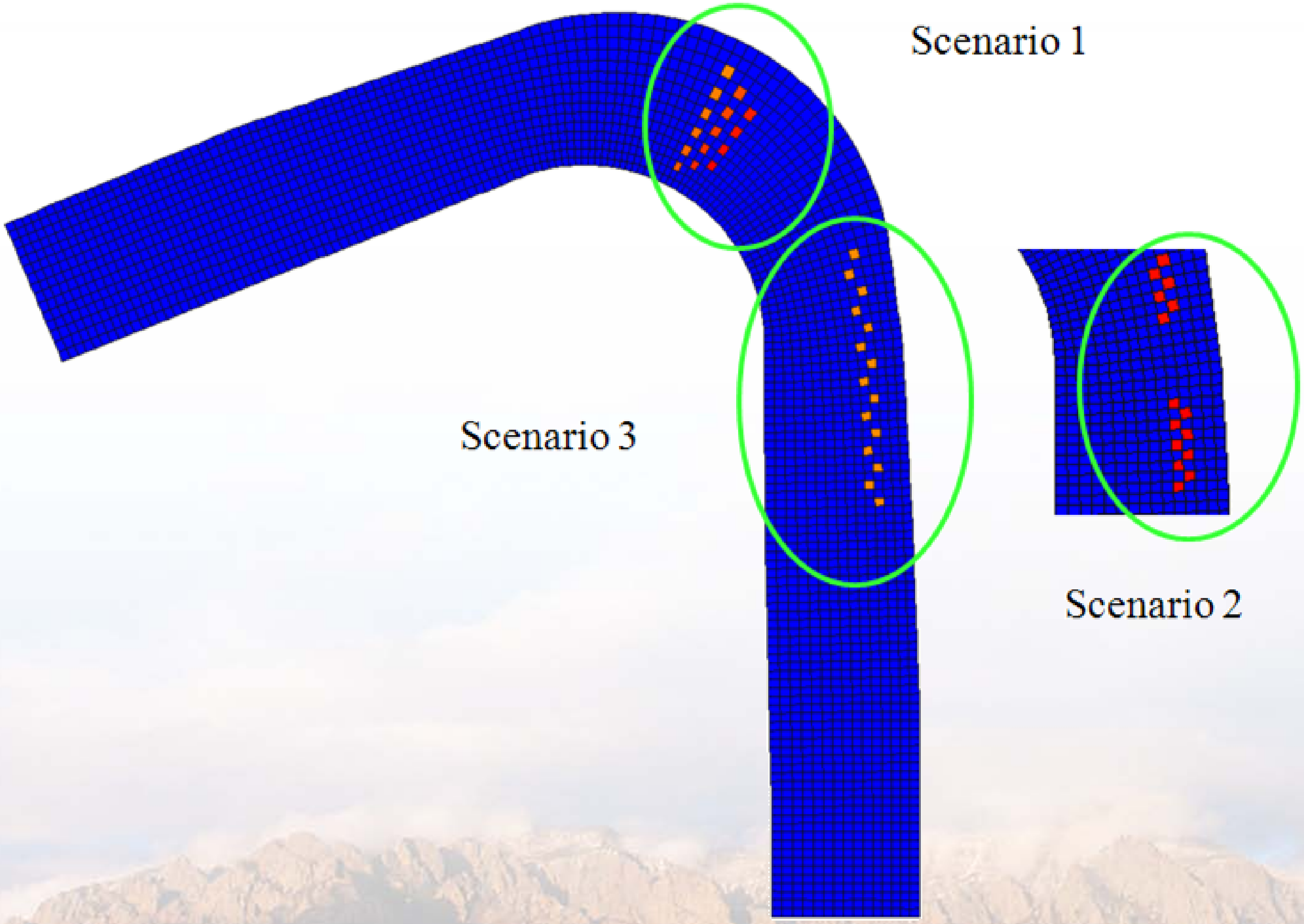
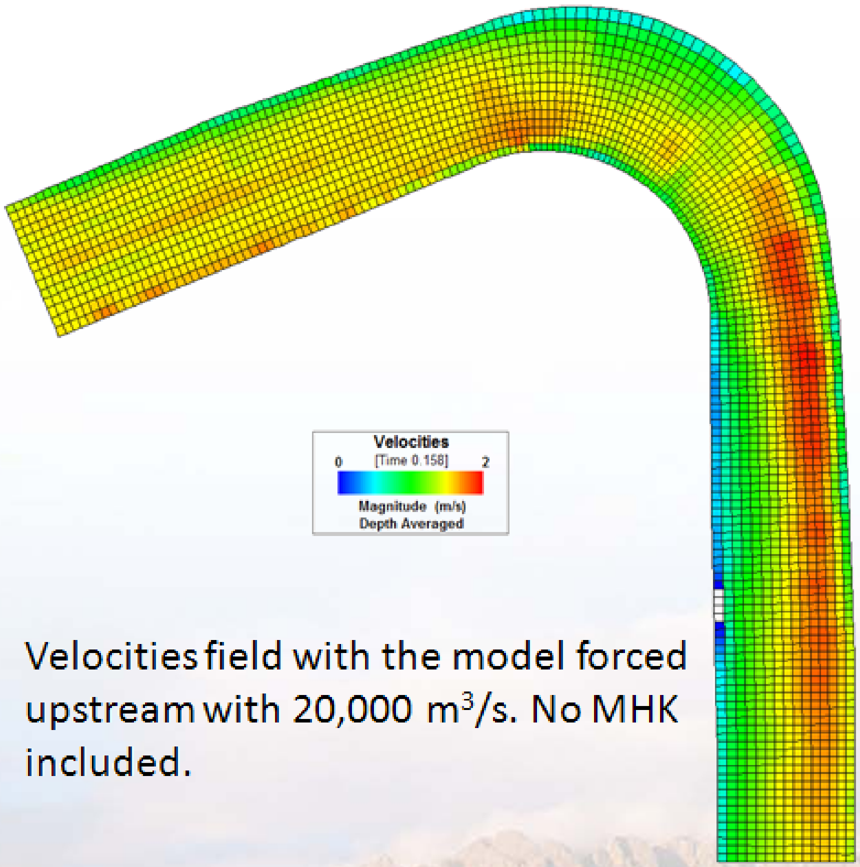
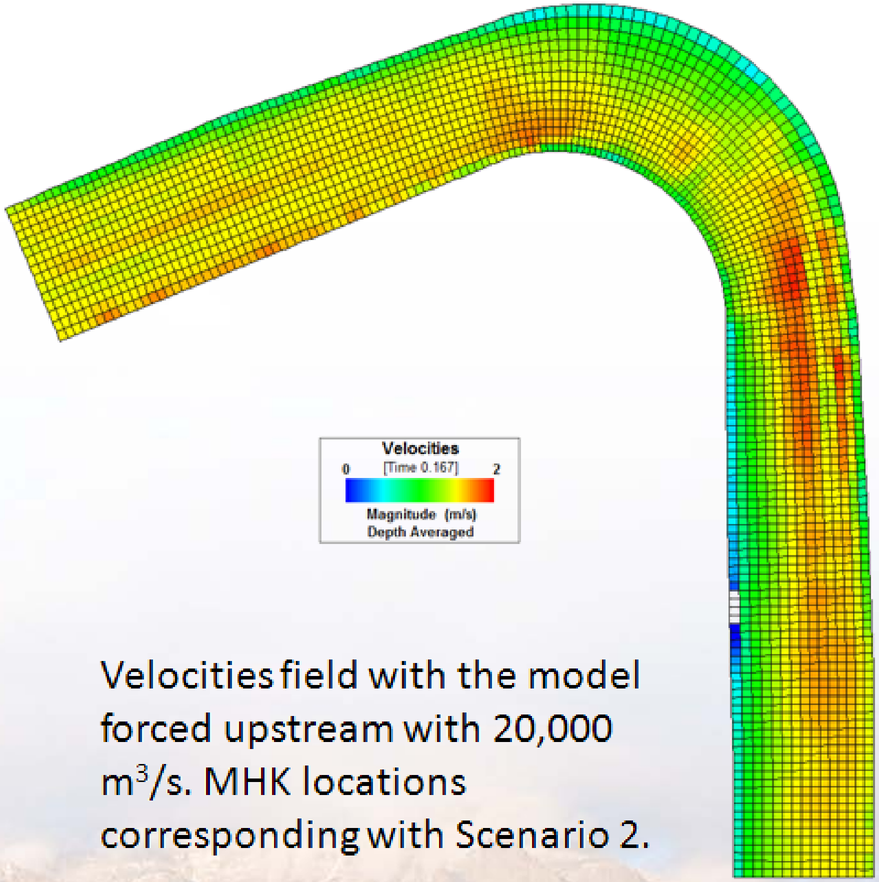


Mississippi River, Scotlandville Bend



Velocities field with the model forced upstream with 20,000 m^3/s. No MHK included.

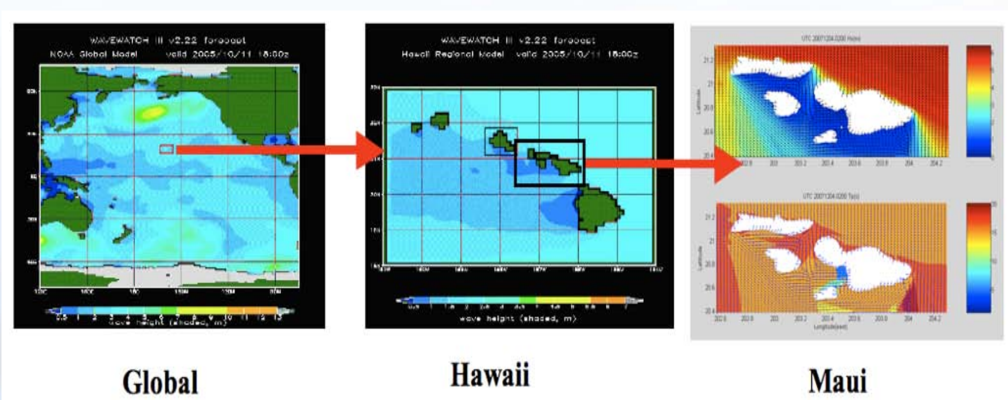


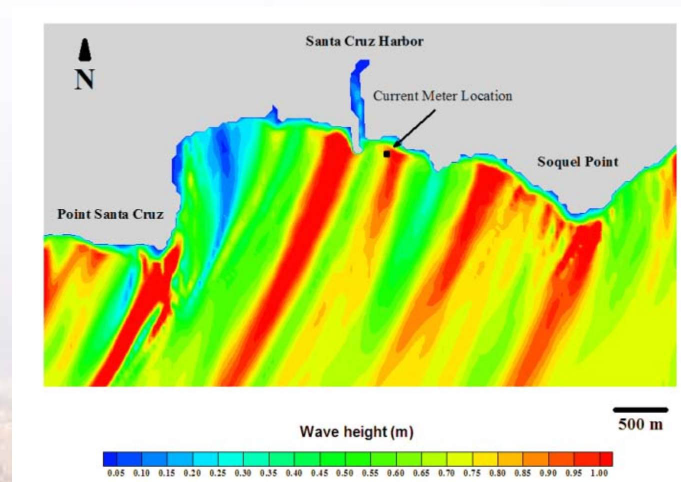
Velocities field with the model forced upstream with 20,000 m^3/s. MHK locations corresponding with Scenario 2.

Wave Environment Hydrology

SWAN and WaveWatchIII – Wave Modeling

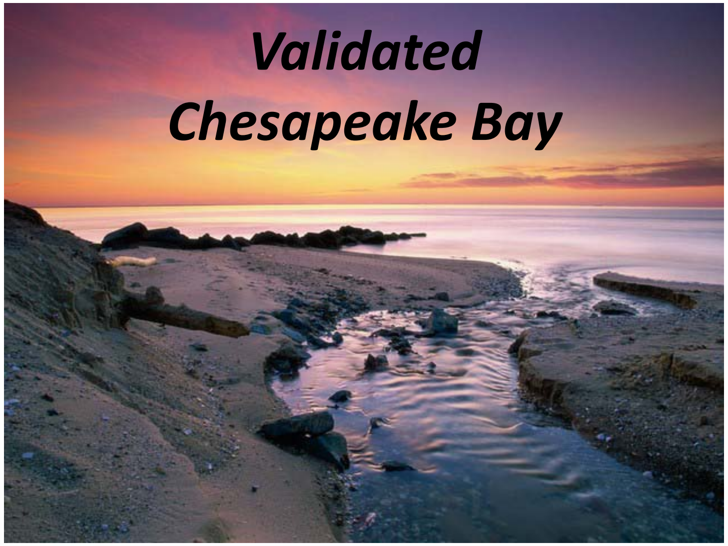
- **NWW3 – NOAA operational wave model**
  - Generate deepwater offshore wave conditions
- **SWAN – Simulating WAves Nearshore (Delft)**
  - Propagation of deepwater waves into nearshore
    - Refraction, diffraction, shoaling, energy dissipation, breaking

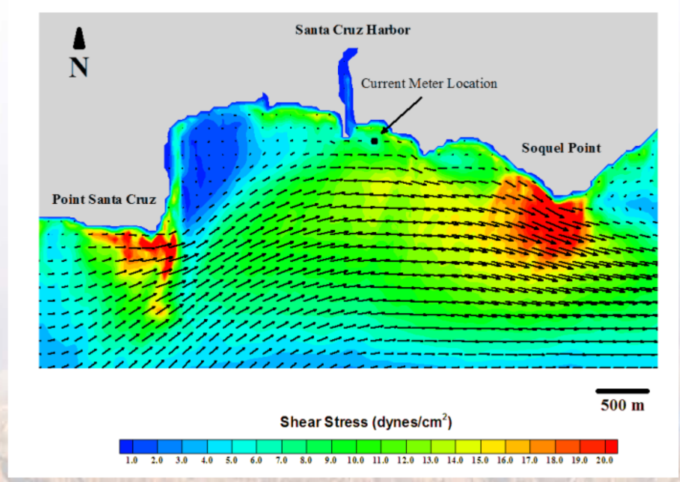




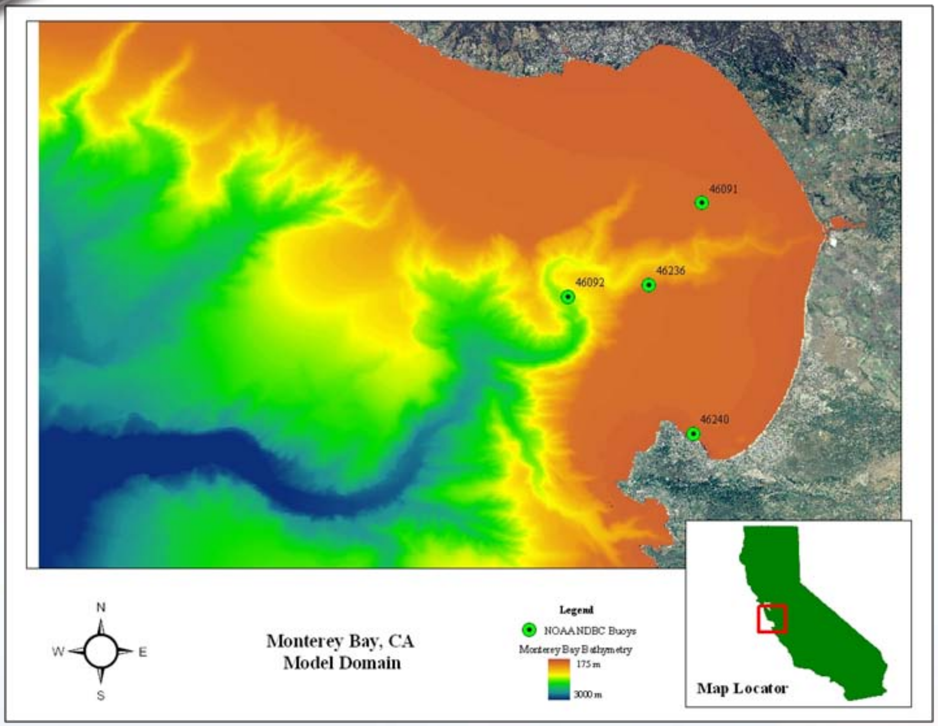
EFDC – Flow and Transport

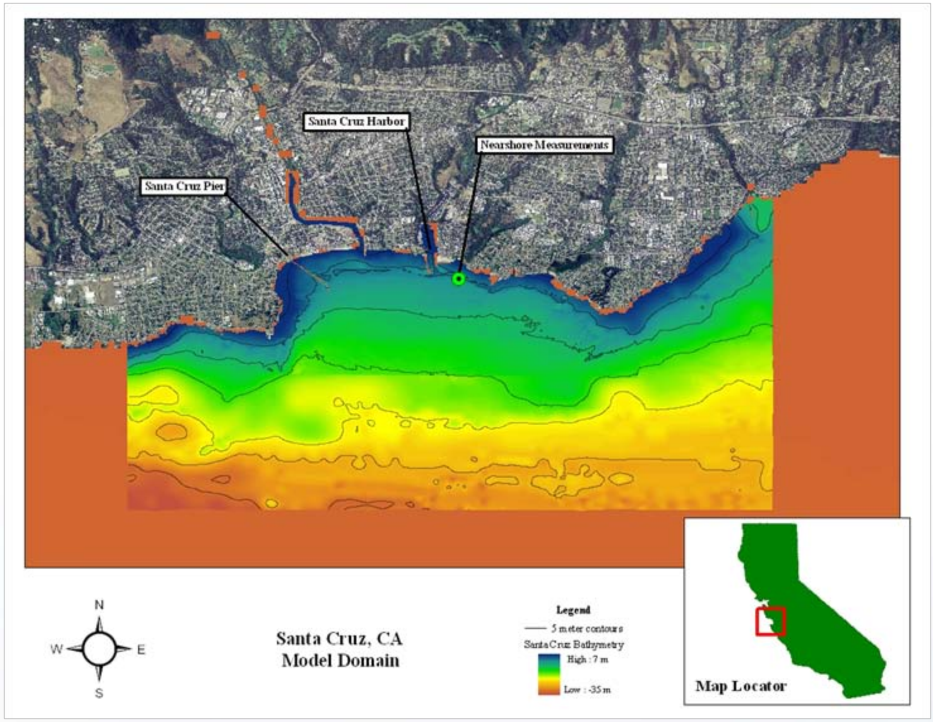
- **EPA open-source code**
- **Curvilinear orthogonal grid**
- **Coupled-equation solution**
  - Mass conservation
  - Momentum conservation
  - *K-ε conservation*
  - Temperature transport
  - Salinity transport
  - Dye transport
- **Links with SWAN time-series**

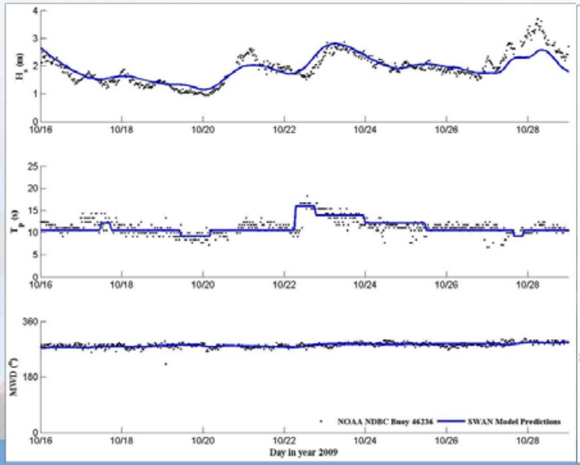


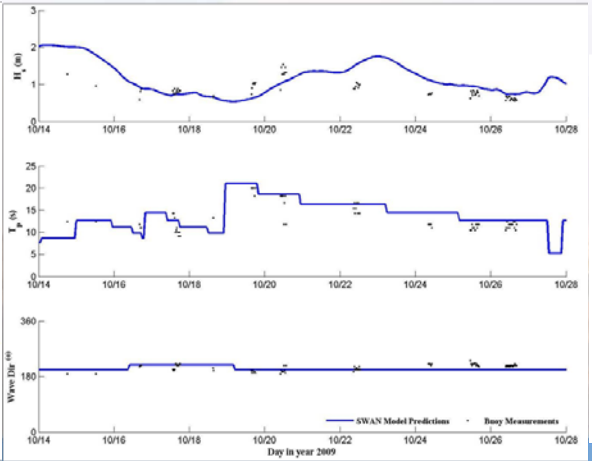


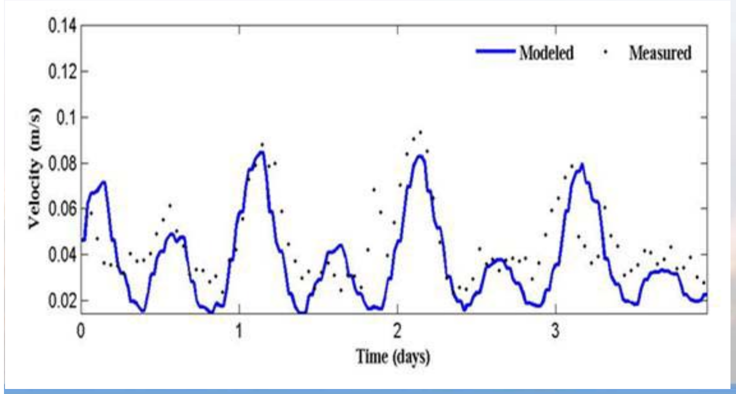
Wave and Circulation Model – Santa Cruz











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*SNL also modeling and testing activities in Reference Model and Market Acceleration tasks

Extra Slides

SEDZLJ – Sediment Dynamics

<u>Flumes necessitated the development of improved model</u>

- Simultaneous treatment of cohesive and non-cohesive sediments
- Erosion – Based on site-specific flume data
- Transport – Bedload and suspended load
- Bed armoring and consolidation
- Bed-slope effects
- Multiple sediment size classes
- Slope dependence
- Cohesive bed consolidation
- Morphological feedback to flow
- 3-D sediment bed

Sediment Model – Cedar Lake

Total Suspended Sediment Concentraion (mg/L)