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Description of the Three-Dimensional Hydrodynamic Model: Environmental Fluid Dynamics Code

Craig Jones
Sea Engineering, Inc.

Jesse Roberts
Sandia National Laboratories

Scott James
Exponent, Inc.

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Outline

- Development History
- Capabilities
- Hydrodynamic Modeling
- Example EFDC Applications:
  - Straight Channel
  - San Francisco Bay

ENVIRONMENTAL FLUID DYNAMICS CODE (EFDC)

- The EFDC model is a public-domain surface-water modeling system incorporating fully integrated hydrodynamics
- EFDC can be used for 1D, 2D, or 3D simulations of rivers, lakes, estuaries, coastal regions

EFDC Development History

- Developed by Dr. John Hamrick at the Virginia Institute of Marine Science (VIMS) with primary support from the State of Virginia
- In 1996, the pubic-domain version was released with Primary Support from U.S. EPA
- Currently used by federal, state and local agencies, consultants, and universities

EFDC Capabilities

- EFDC resolve circulation and transport in complex environments
  - Estuaries, rivers, lakes, and coastal waters

- EFDC Simulates:
  - Scalar transport:
    - Dye-tracer
    - Temperature
    - Water-quality variables
  - Density stratification due to:
    - Salinity
    - Temperature
    - Sediment concentration

EFDC Capabilities

- Directly coupled sediment and contaminant transport and fate model
  - Multiple sub-model options
- Simulates wetting and drying of flood plains, mud flats, and tidal marshes
- Integrated near-field mixing zone model (jet and plume injections)
- Recirculating boundary conditions

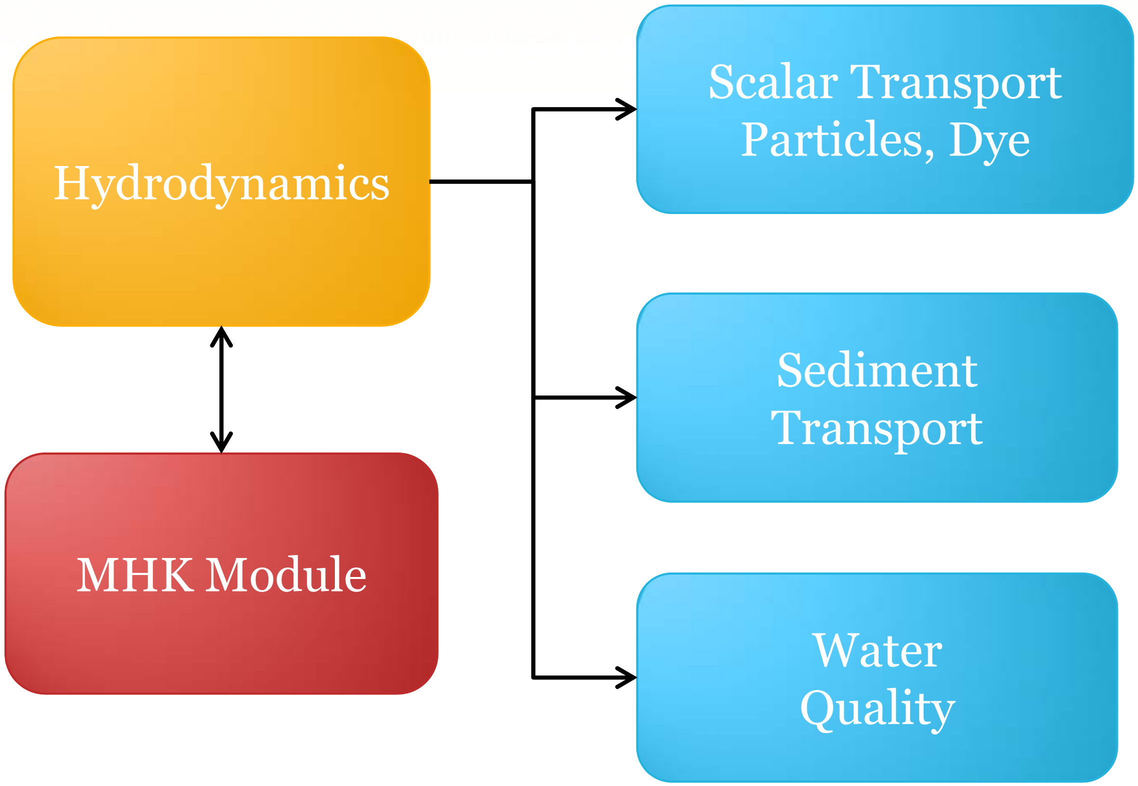
EFDC Capabilities

- Simulates hydraulic control structures such as dams and culverts
- Simulates wave boundary layers and wave-induced currents
- Available pre-processing and post-processing software EFDC Explorer
  - Free and proprietary versions (Dynamic Solutions LLC)

SNL-EFDC

- SNL-EFDC is an extension of EFDC for predicting effects of MHK devices
- Upgrades to the water-quality routines
- Significant upgrades to the sediment transport routines of SNL-EFDC
  - When used with accurate measurements of erosion and transport mode provides realistic predictions of sediment transport
  - Applications of this algorithm have shown excellent agreement between both theoretical predictions and observations

Basic SNL-EFDC Structure



Example of Peer-Reviewed EFDC Applications

- Rivers – Potomac River (VA), Fox River (WI), Flint (AL), Housatonic (MA), Chattahoochee (GA), Los Angeles (CA), Penobscot River (ME)

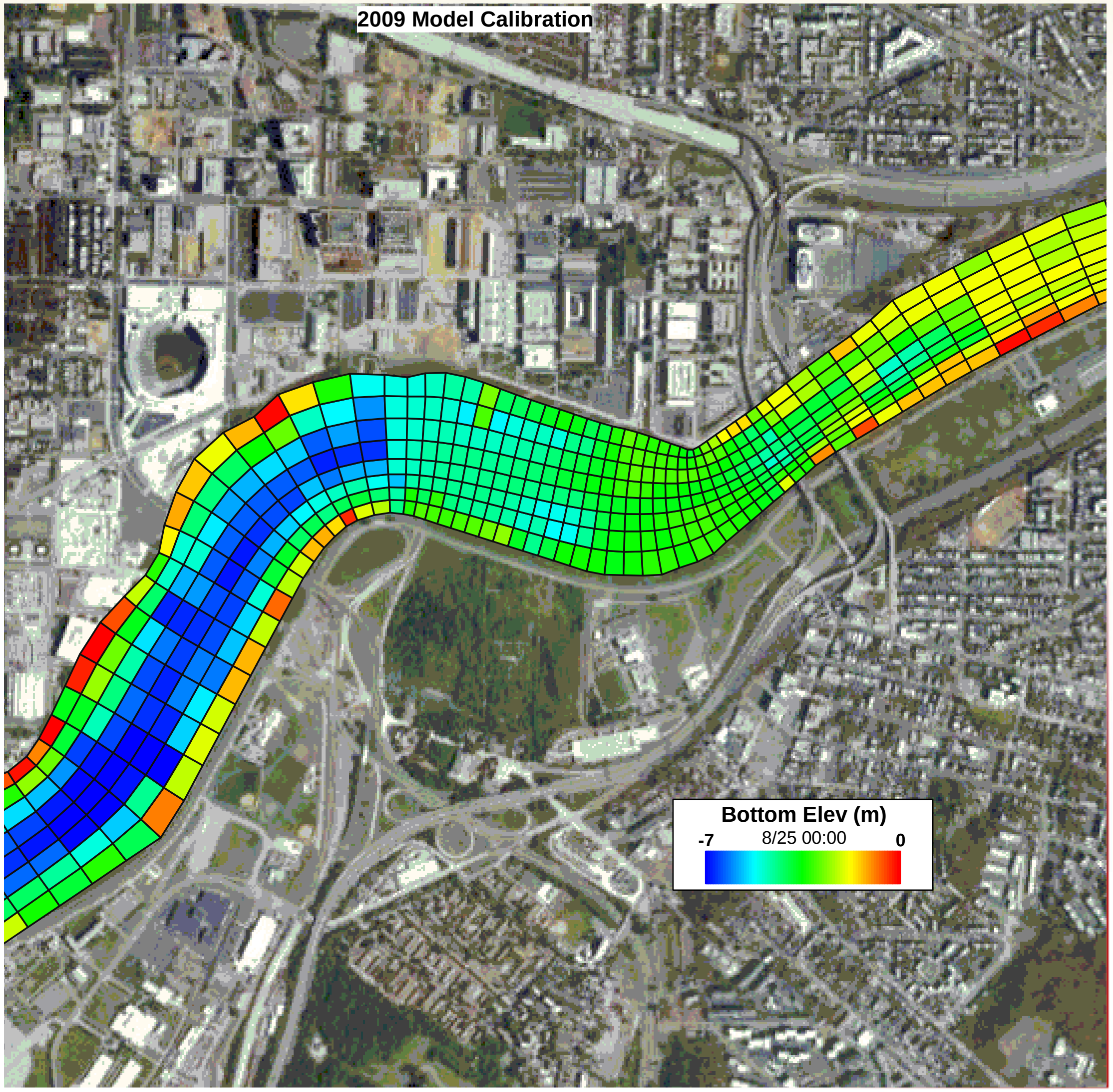
- Lakes – Cedar Lake (IL), Lake Okeechobee (FL), Lake Jordan (NC), Coosa River Reservoirs (AL), Lake Allatoona (GA), Hartwell Reservoir (GA/SC), East River (NY)

- Estuaries - Mobile Bay (AL), Neuse River (NC), Savannah River/Harbor (GA), Charleston Harbor (SC), St. Johns River (FL), Lower Duwamish Waterway (WA), Curonian Lagoon (Lithuania), Chesapeake Bay (VA), Peconic Bays (NY), Cobscook Bay (ME), San Francisco Bay (CA)

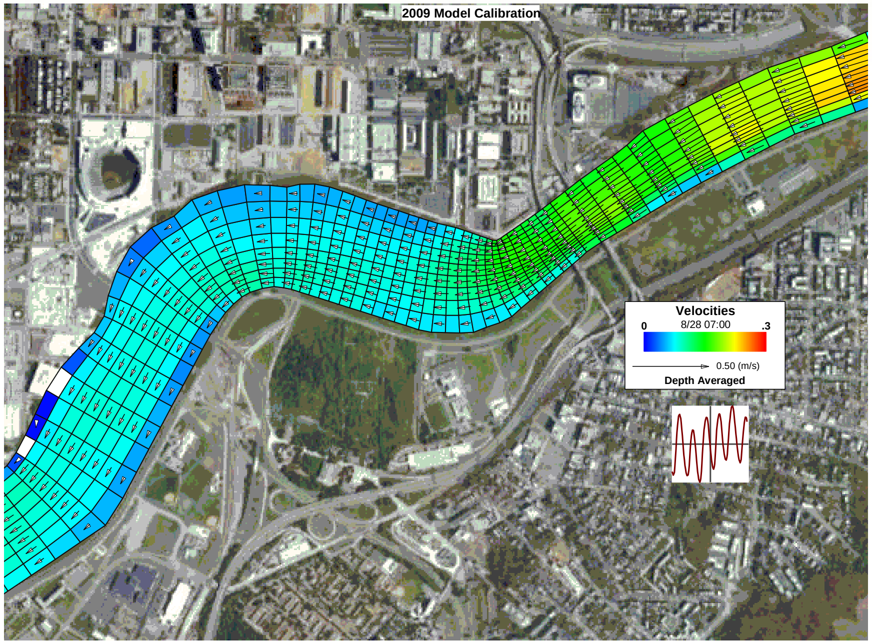
- Coastal – Oahu (HI), Santa Cruz (CA)

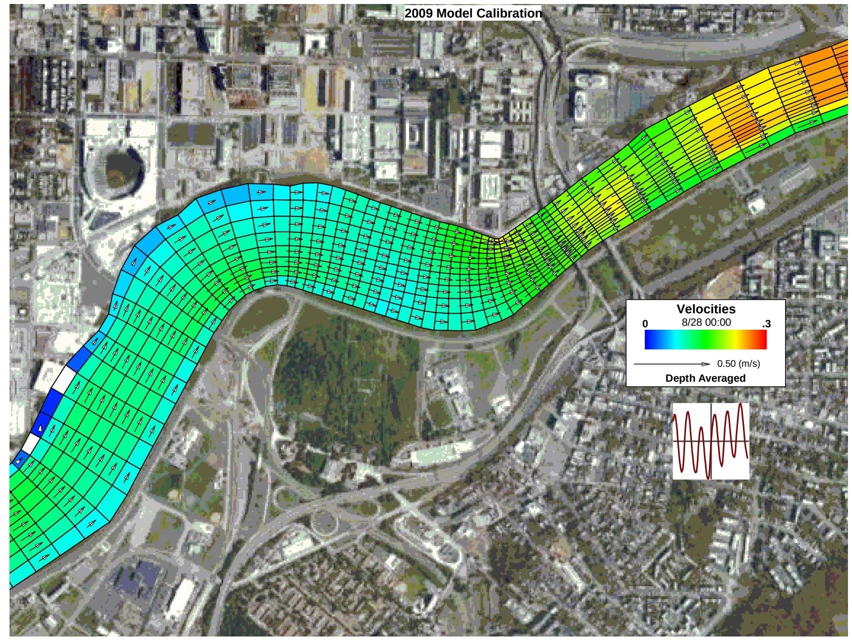
Channel Flow

Curvilinear grids can be used to more accurately represent sinuous channels.



Tidal Channel Flow

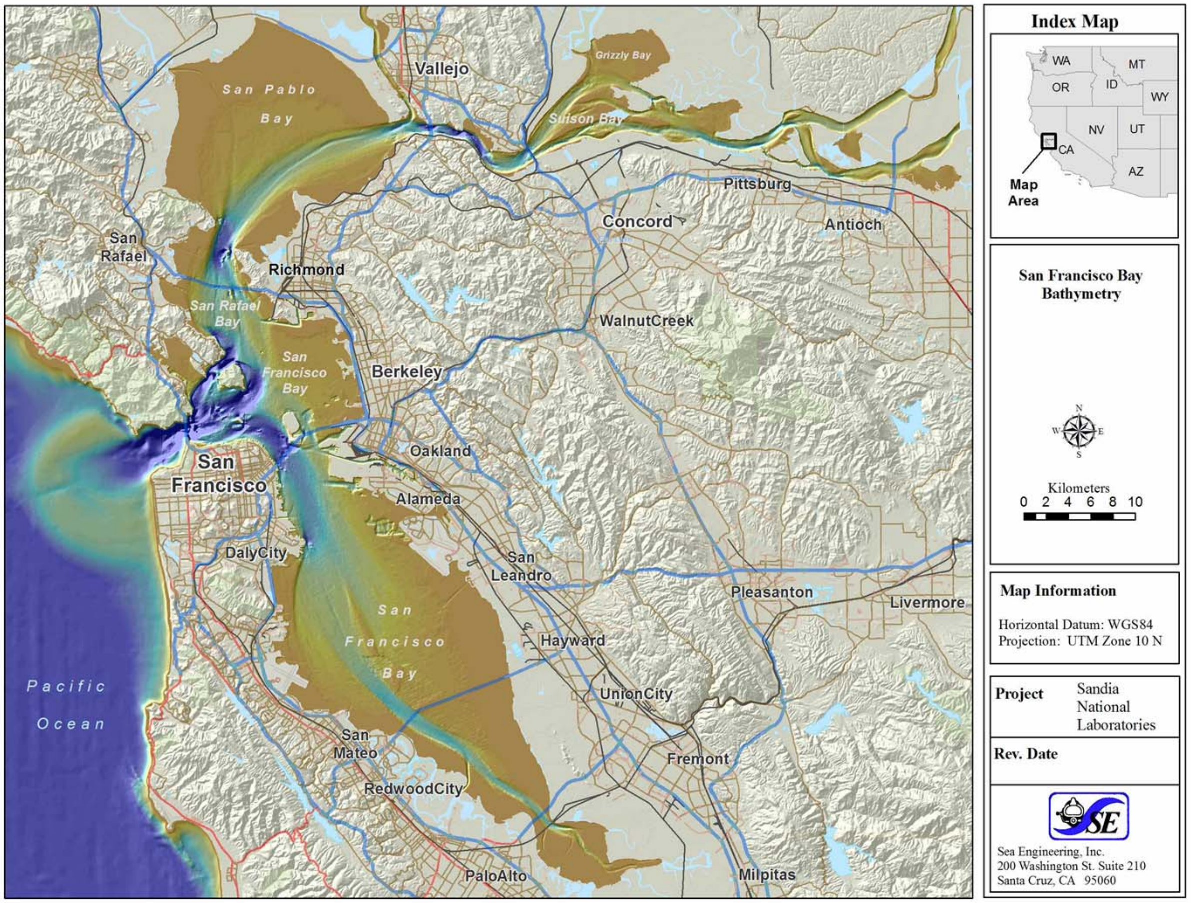




Ebb and flood velocity structure can be accurately simulated in estuarine systems.

San Francisco Bay

GIS is typically used to define shorelines and bathymetry for complex grid development.



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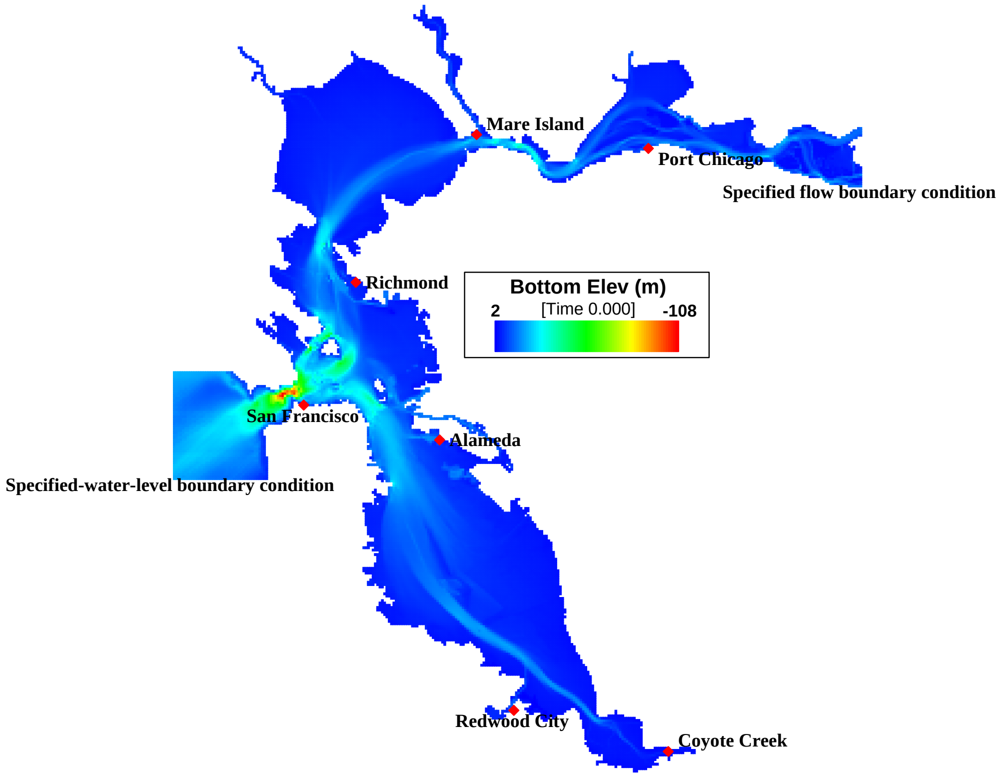
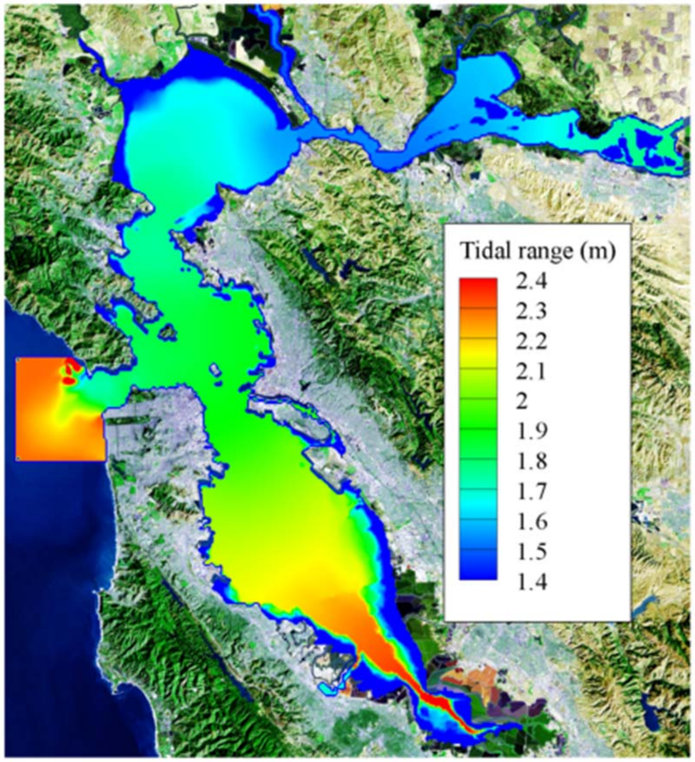
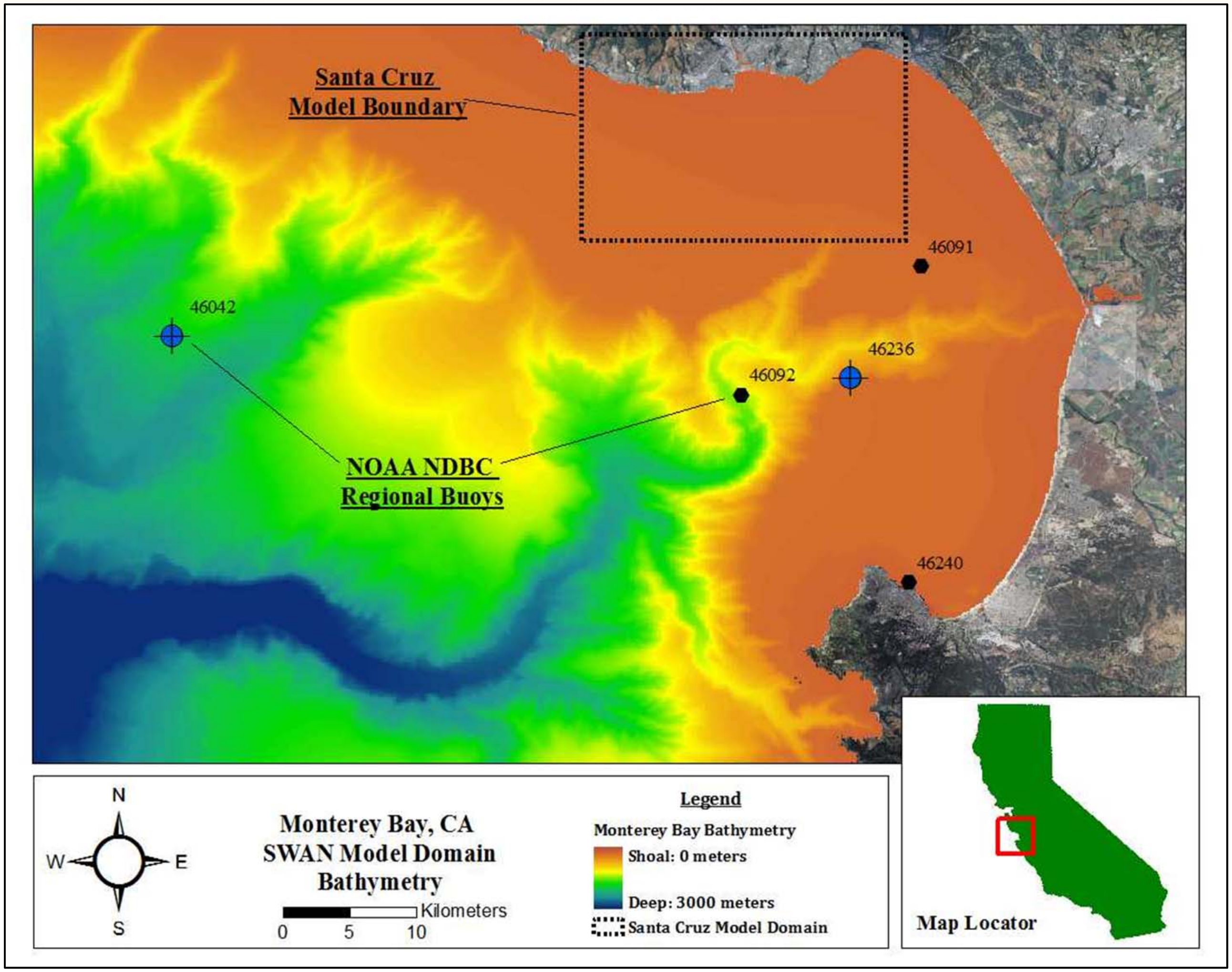
San Francisco Bay



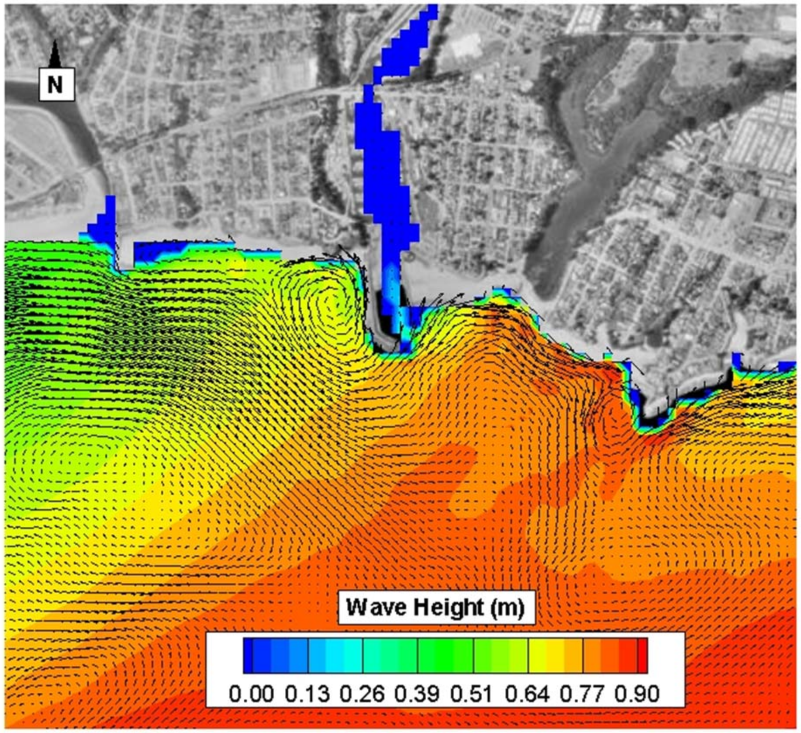


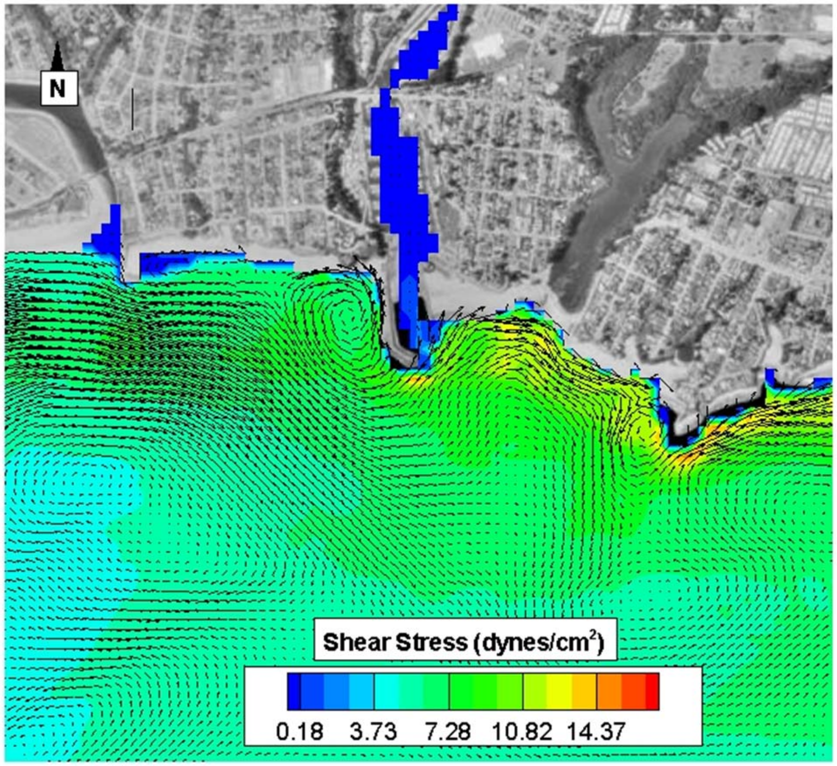
With accurate boundary conditions, a well calibrated model can accurately reproduce hydrodynamics in the system.

Santa Cruz Bight

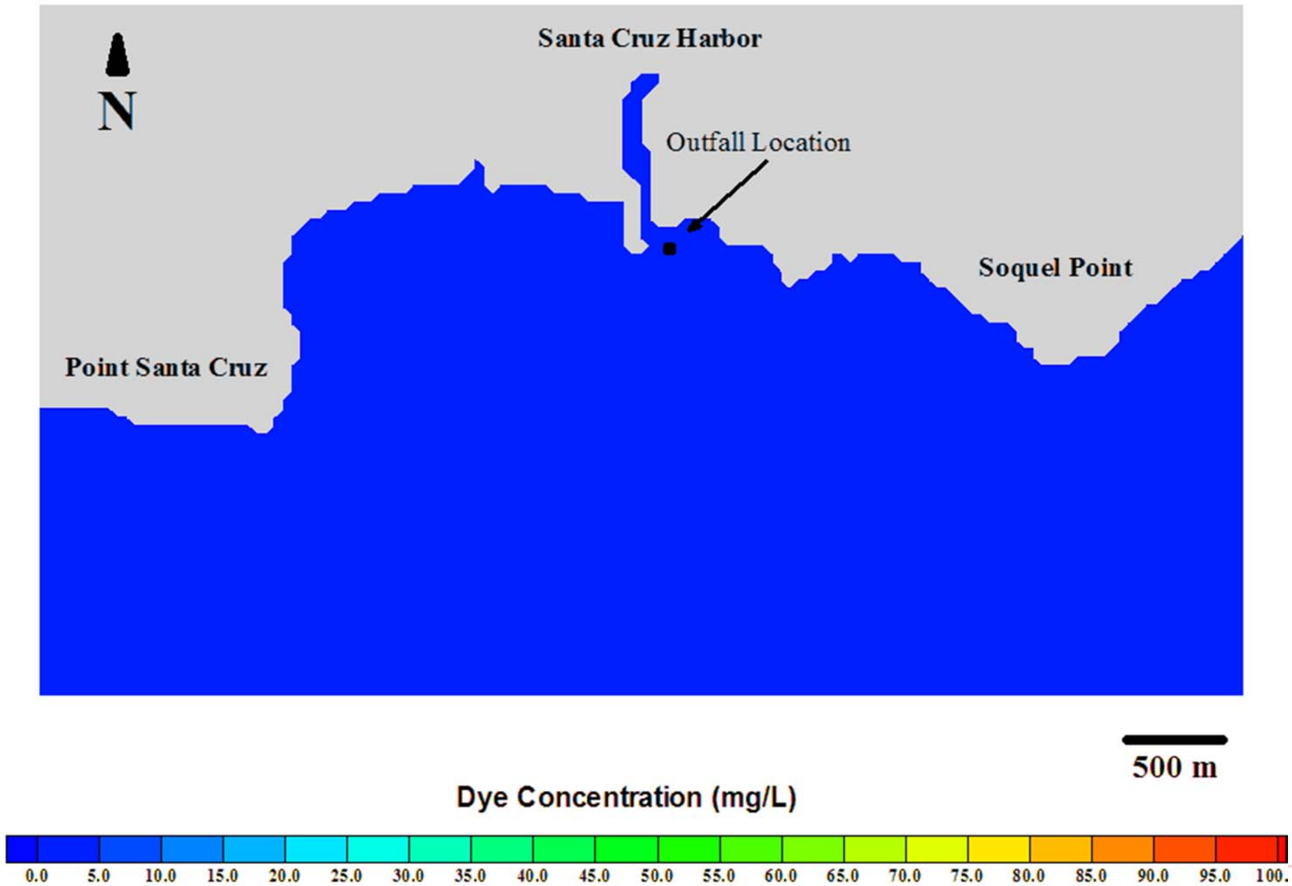


Santa Cruz Bight





Santa Cruz Bight



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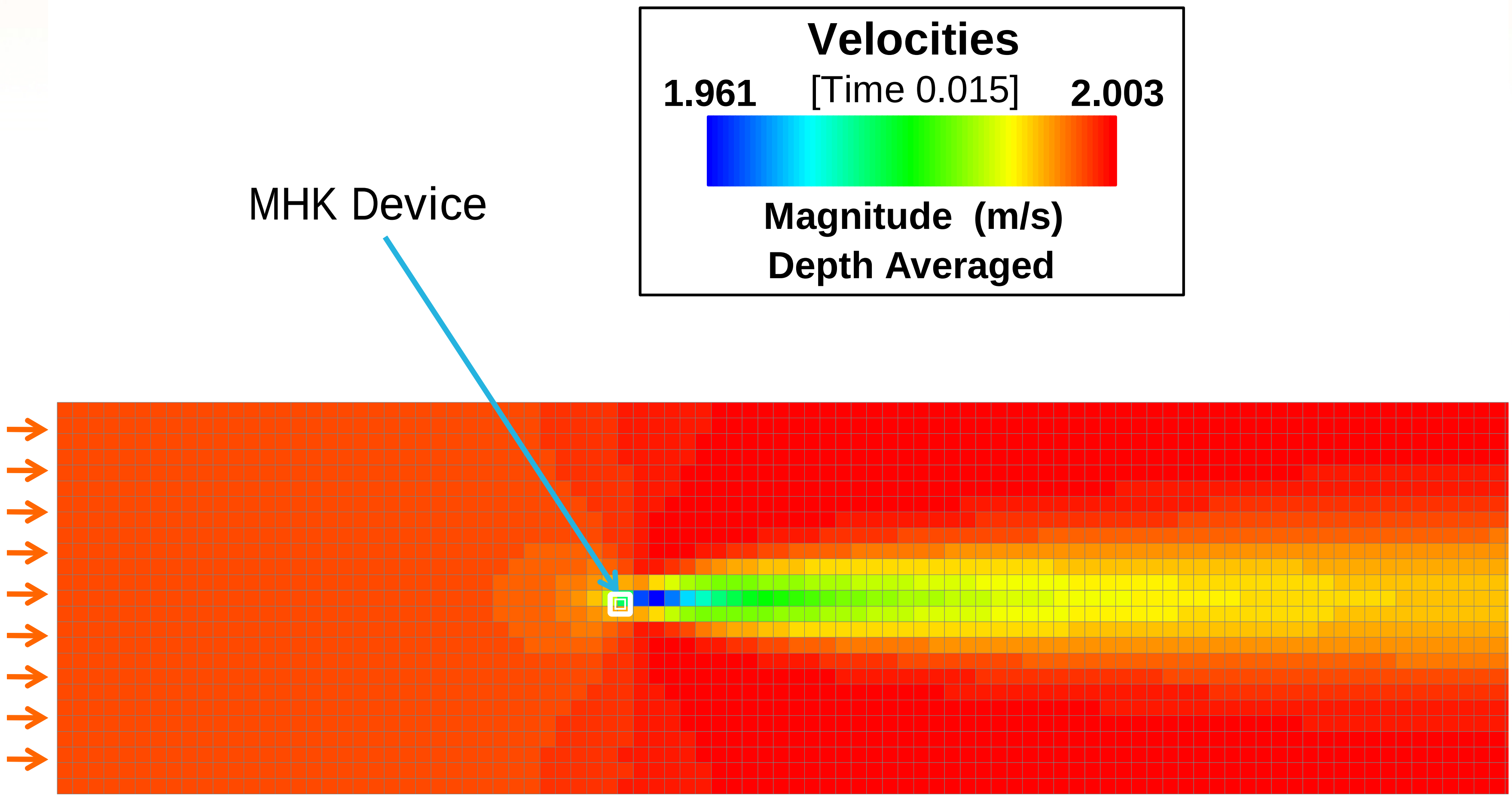
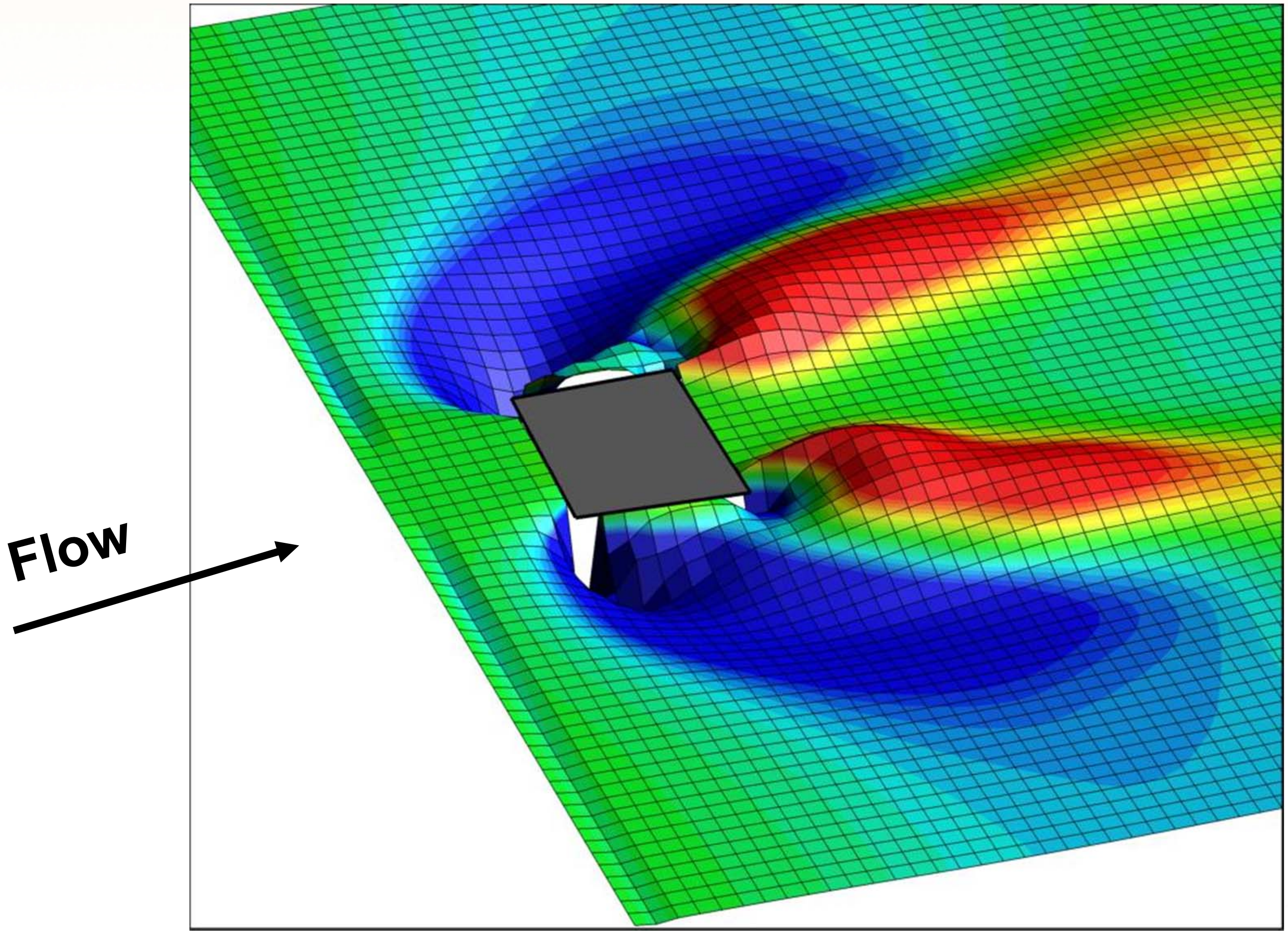
MHK Modeling

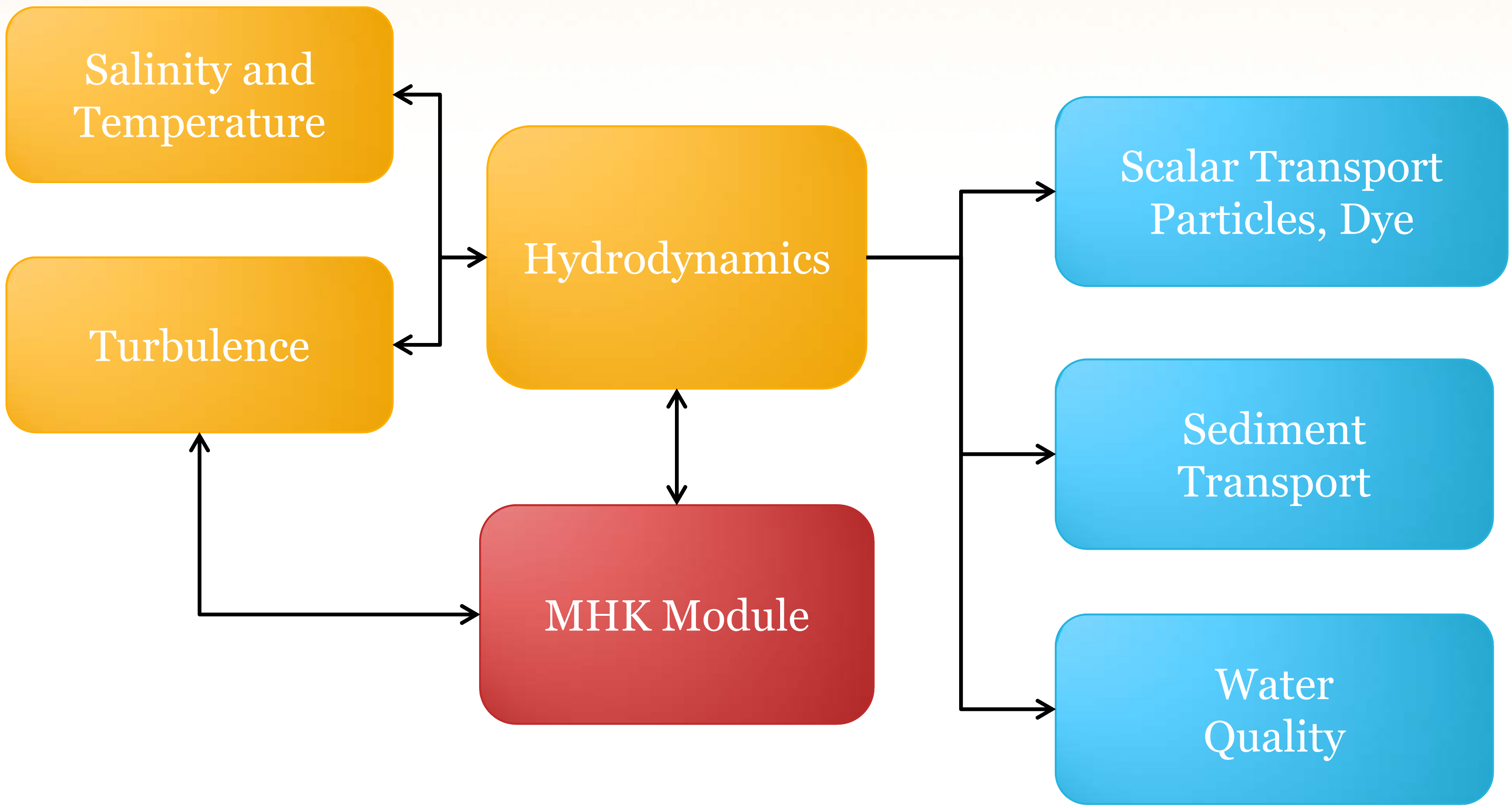


Scour Modeling



Bathymetric profile after a simulated scour event.

Basic EFDC Structure

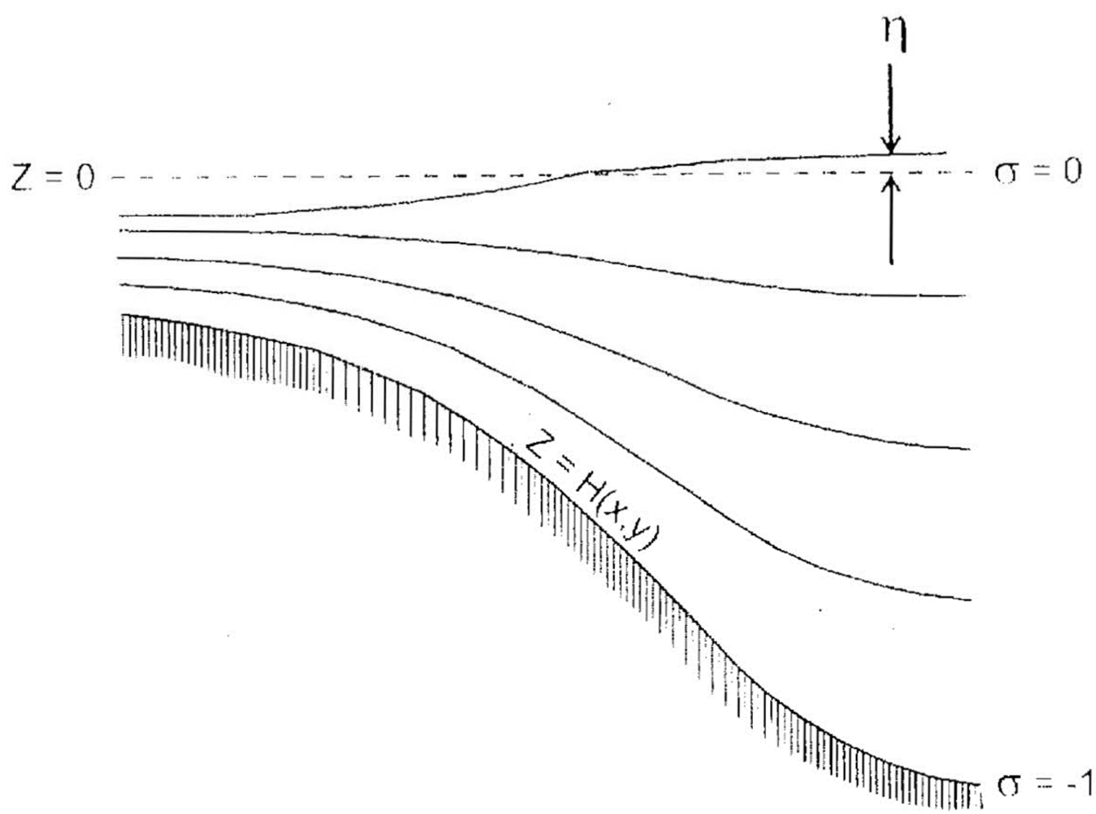


EFDC Hydrodynamic Module

- Fully 3D with 2D options
- Boundary-fitted curvilinear or Cartesian grids
  - σ-level or stretched bathymetry-following grid in the vertical
- Includes turbulence closure model (Mellor and Yamada, 1982)
- Finite difference, semi-implicit solution

EFDC Hydrodynamic Module - Grid

In EFDC, the sigma (σ or stretched) transformation is used to develop a “bottom following” grid.



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EFDC Hydrodynamic Module

- The equations of motion and transport are turbulence-averaged.
- A statistical approach is applied, where values are decomposed into mean and fluctuating values for solution.
- Dispersion terms are introduced to the equations for flow to represent the turbulence terms.
- The turbulent equations of motion are formulated to use the Boussinesq approximation for variable density (i.e., salinity and temperature stratification).

EFDC Atmospheric Coupling

- Wind stresses can drive fluid motion (mixing and transport)
- Atmospheric coupling can drive temperature transport
  - Solar radiative heating (cloud cover considered)
  - Heat exchange as a function of air temperature and wind speed
  - Evaporative cooling
  - Long-wave radiative heat is emitted from the water column
- Atmospheric pressure affects water surface elevation
- Heat exchange with the sediment bed

EFDC Hydrodynamic Module

Three-dimensional continuity

$$H = h + \eta$$

$$\frac{\partial H}{\partial t} + \frac{\partial Hu}{\partial x} + \frac{\partial Hv}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Conservation of momentum - *x* component (Cartesian)

Advection, Coriolis

$$\frac{\partial Hu}{\partial t} + \left[\frac{\partial Huu}{\partial x} + \frac{\partial Hvu}{\partial y} + \frac{\partial wu}{\partial z}\right] - fHv =$$

$$-H\frac{\partial p}{\partial x} + \left(\frac{\partial z_b^*}{\partial x} + z\frac{\partial H}{\partial x}\right)\frac{\partial p}{\partial z} + \frac{\partial}{\partial z}\left(\frac{A_V}{H}\frac{\partial u}{\partial z}\right) + \frac{\partial}{\partial x}\left(HA_H\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial y}\left(HA_H\frac{\partial u}{\partial y}\right) - c_p D_p\left(u^2+v^2\right)^{1/2} u$$

Pressure, Buoyancy, Vertical-momentum diffusion, Horizontal-momentum diffusion, Vegetative resistance

x-Momentum Equation

Coriolis force	$-fHv$
Buoyancy	$\frac{\partial p}{\partial z} = -gH\frac{\rho - \rho_0}{\rho_0}$
Momentum diffusion (Vertical and Horizontal)	$\frac{\partial}{\partial z}\left(\frac{A_V}{H}\frac{\partial u}{\partial z}\right) + \frac{\partial}{\partial x}\left(HA_H\frac{\partial u}{\partial x}\right)$
Vegetative resistance	$-c_p D_p \left(u^2 + v^2\right)^{1/2} u$

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EFDC Hydrodynamic Module

- The vegetation resistance where c_p is a resistance coefficient and D_p is the projected vegetation area normal to the flow

$$-c_p D_p \left(u^2 + v^2\right)^{1/2} u$$

- By direct analogy, MHK devices remove momentum from the flow just like vegetative resistance
- MHK devices also include source terms for turbulence transport (more on this later)

EFDC Turbulence Transport

- Horizontal turbulent diffusivity (A_H) is determined independently using Smagorinsky's (1963) subgrid scale closure formulation

- The second moment turbulence closure model developed by Mellor and Yamada (1982) is used to determine the values of vertical diffusivity (A_v)

$$A_v = \phi_A A_0 q l$$

- The Mellor and Yamada model relates the vertical turbulent viscosity and diffusivity to the turbulent intensity (q) a turbulent length scale (l) and a turbulent intensity and length scaled based Richardson number (R_q)

EFDC Turbulence Transport

- The turbulence intensity (q^2) and length scale (l) are determined by solving the standard transport equations

$$\frac{\partial Hq^2}{\partial t}+\frac{\partial Huq^2}{\partial x}+\frac{\partial Hvq^2}{\partial y}+\frac{\partial wq^2}{\partial z}$$
$$=\frac{\partial}{\partial z}\left(\frac{A_q}{H}\frac{\partial q^2}{\partial z}\right)-2\frac{Hq^3}{B_1 l}+2\left\{\frac{A_v}{H}\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]+\eta_p c_p D_p\left(u^2+v^2\right)^{3/2}+gK_v\frac{\partial b}{\partial z}\right\}+Q_q$$

$$\frac{\partial Hq^2 l}{\partial t}+\frac{\partial Huq^2 l}{\partial x}+\frac{\partial Hvq^2 l}{\partial y}+\frac{\partial wq^2 l}{\partial z}$$
$$=\frac{\partial}{\partial z}\left(\frac{A_q}{H}\frac{\partial q^2 l}{\partial z}\right)-\frac{Hq^3}{B_1}\left\{1+E_2\left(\frac{l}{\kappa Hz}\right)^2+E_3\left[\frac{l}{\kappa H\left(1-z\right)}\right]^2\right\}$$
$$+E_1 l\left\{\frac{A_v}{H}\left[\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2\right]+\eta_p c_p D_p\left(u^2+v^2\right)^{3/2}+gK_v\frac{\partial b}{\partial z}\right\}+Q_l$$

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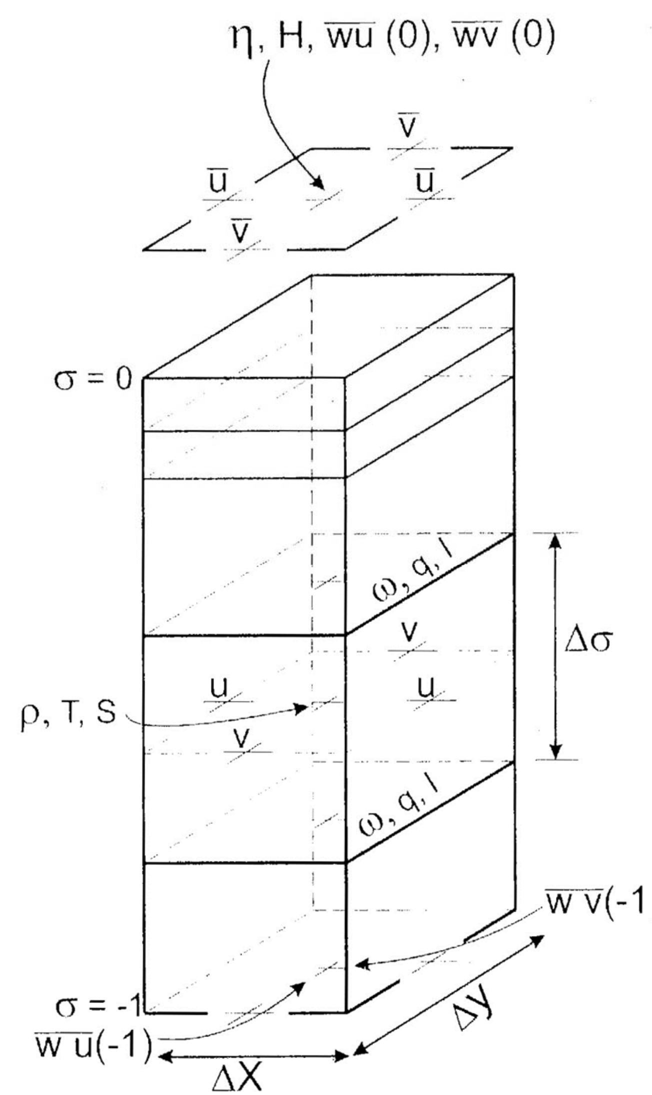
EFDC Hydrodynamic Module Solution Scheme

- The transport equations outlined above are solved on a staggered computation “C” grid using finite differencing
- The velocities are face centered on each cell and then η (i.e., water surface elevation) is solved at the cell center (i.e., node)



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EFDC Hydrodynamic Module Solution Scheme

- For computational efficiency, the solution of the transport equations use a mode-splitting technique common in oceanographic models
- The theory is based on the difference in movement of fast-moving external gravity waves and slower moving internal waves in a system
- Two sets of transport equations are used to obtain a numerical solution:
  - External – Vertically integrated momentum equations are solved more frequently (~1-100 time steps) to obtain an average horizontal velocity and water-surface solution
  - Internal – Vertically resolved momentum equations are solved at the completion of each external solution to resolve changes in the vertical structure of velocity and other water column properties
- The mode-splitting technique provides a robust and efficient solution for the hydrodynamics

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Model Development:

Tiered Approach

- Developing a model in tiers is the most efficient and cost effective approach
- The general approach to the modeling study is outlined at the beginning of the project
- Design of later tiers will be refined as the site becomes better understood

Model Development:

Typical Phased Approach

- **Tier 1**: Data compilation and initial **C**onceptual **S**ite **M**odel development
- **Tier 2**: Hydrodynamic modeling
- **Tier 3**: Transport modeling (dye, temperature, sediment, water quality, MHK)

Tier 1 – Data Compilation and Initial CSM Development

- Compile and analyze available data
- Identify data gaps
- Design and conduct field studies to fill data gaps
  - Measurement of currents, waves, water levels
- Develop initial CSM for hydrodynamics

Tier 2 – Hydrodynamic Modeling

- Develop model
  - Generate model grid and bathymetry
  - Develop boundary conditions for model
  - Initial testing of hydrodynamic model
  - Calibrate and validate hydrodynamic model
- Incorporate MHK
- Evaluate CSM

Hydrodynamic Model:
Typical Data Needs

- Geometry and bathymetry of study area
  - Bathymetry for riverine studies
  - Additional marsh topography in estuarine studies
- Inflows from upstream boundaries and tributaries
- Water-surface elevation at downstream boundaries
- MHK characteristics
- For some studies, additional data needs may include:
  - Temperature
  - Salinity
  - Wind
  - Vegetation properties

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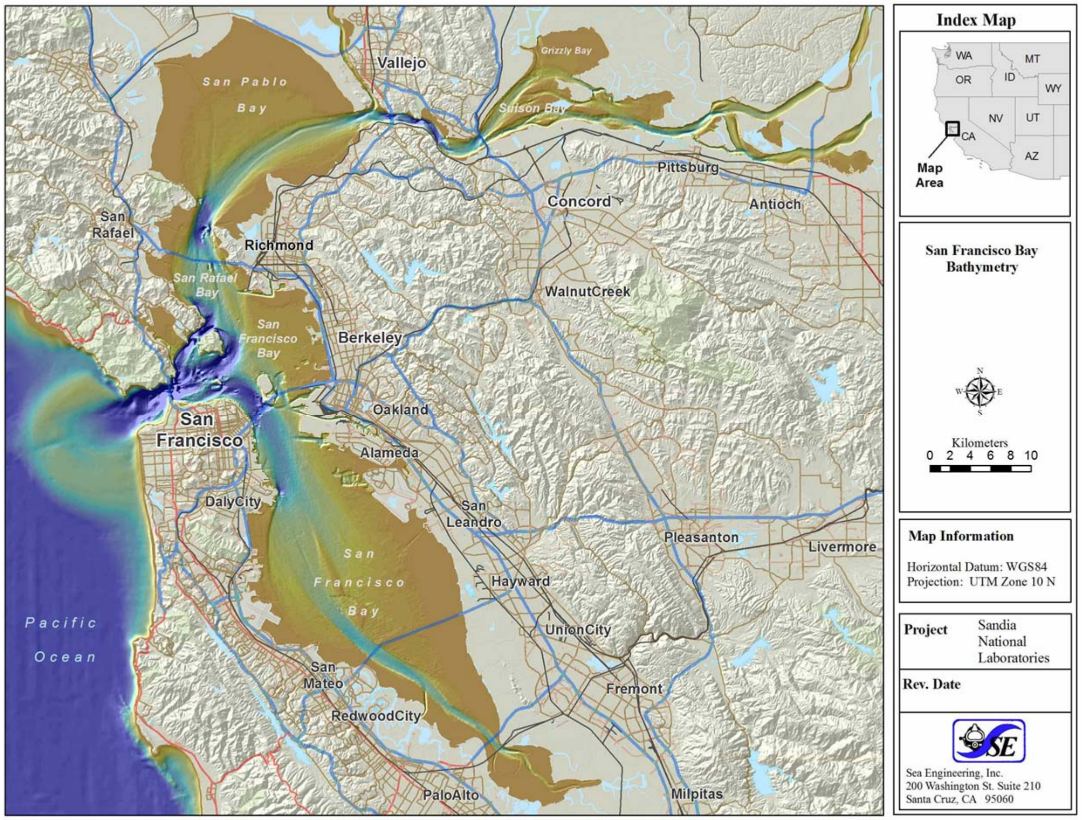
Hydrodynamic Model

Geometry and Bathymetry Data

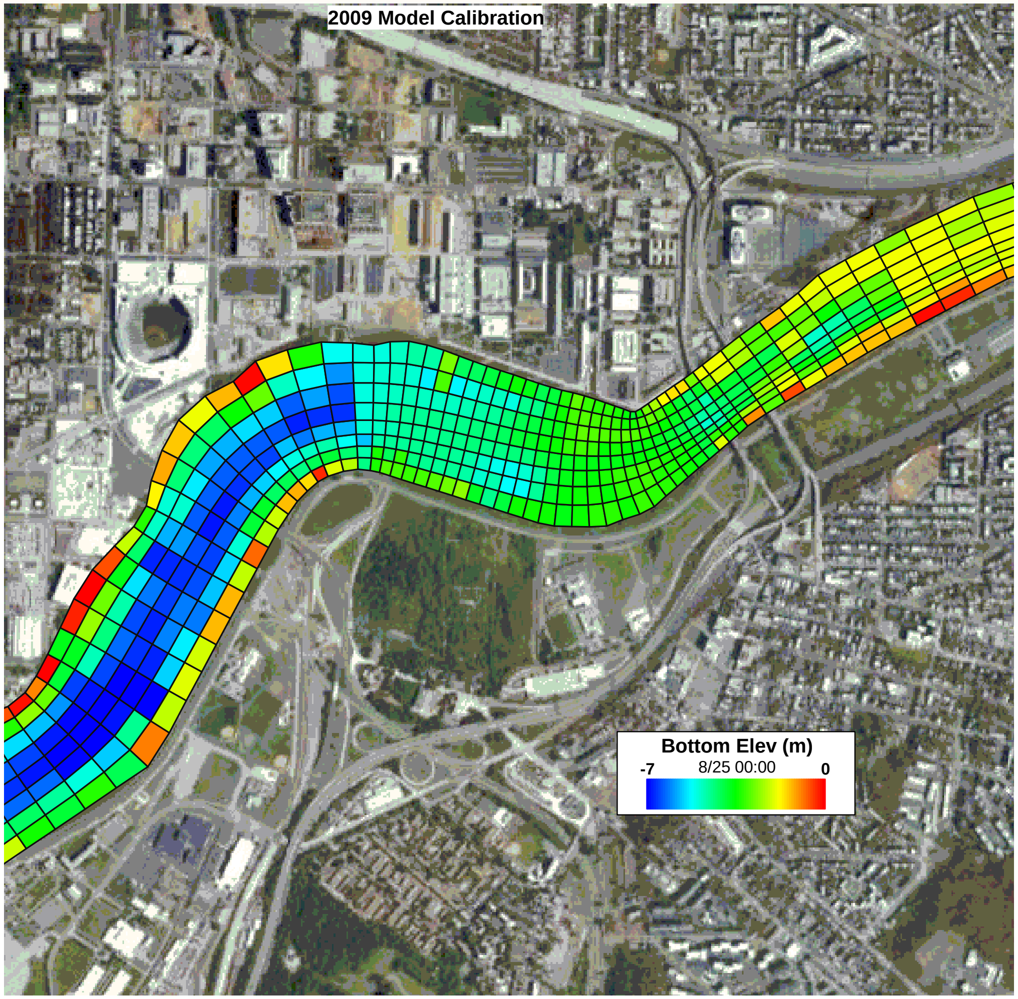
- Shoreline location
- Bathymetry
- Floodplain topography
- Data sources
  - NOAA navigation charts
  - Bathymetry surveys
  - LIDAR surveys



Hydrodynamic Model Development

Numerical Grid Generation

- Determine extent of model domain
  - Upstream and downstream boundaries
- Type of numerical grid depends on geometry of study area
  - Rectangular grid
  - Curvilinear grid
- Need to consider study objectives and questions when designing the numerical grid
  - Long-term, multi-year simulations
  - Areas of special interest
  - Spatial scale of remedial areas



Hydrodynamic Model

Boundary Conditions

- Data sources
  - USGS gauging stations
  - NOAA tidal stations
  - Published field studies
    - Local Universities
    - USACE
    - USGS
    - NOAA
  - Special field studies

Hydrodynamic Model

Initial Model Testing

- Quality control
  - After developing input files for upstream and downstream BCs, generate plots of the model inputs and compare to original data
- Determine maximum time-step for numerical stability
  - May be flow dependent
- Conduct short simulations over a wide range of flow and tidal conditions and verify results
  - For floodplain and inter-tidal areas, ensure that wetting/drying of grid cells is working properly
  - Animate results to examine entire study area

Hydrodynamic Modeling Study

- Conduct a complete modeling study
  - Model calibration with appropriate data sets
  - Model validation using “blind” simulations
  - Model sensitivity testing

- Evaluate appropriateness of MHK parameters
  - Are MHK effects reasonable?
  - Is there any way to design field studies to validate?

Refine Models

- Refine conceptual site models and numerical models to address project questions as needed
- Strike a balance