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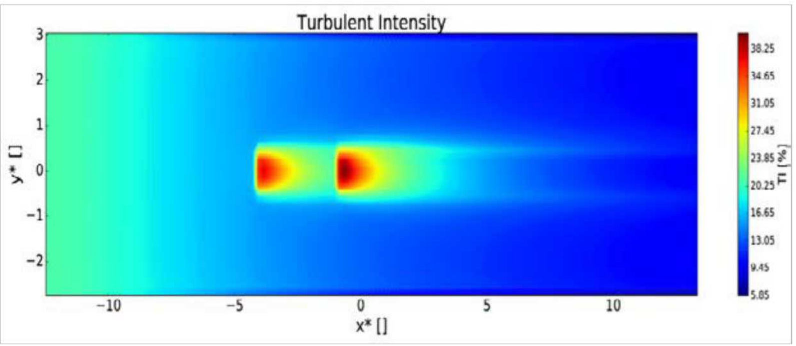


Intro to Current Energy Converter (CEC) Modeling with SNL-Delft3D-CEC

Sandia National Laboratories

Water Power Program

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Background:
Sandia National Laboratories

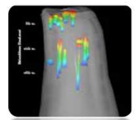
History of Sandia Energy Programs

Sandia National Laboratories


Sandia was born as a nuclear weapons (NW) engineering laboratory with deep science and engineering competencies

Energy crisis of the 1970s spawned the beginning of significant energy work

Strategic Petroleum Reserve -geologically characterizing salt domes to host oil storage caverns



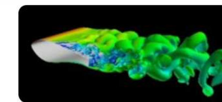
DOE's Tech Transfer Initiative was established by Congress in 1991

CRF & Cummins partner on their newest diesel engine

Advent Solar

Energy Policy Act of 2005

Joint BioEnergy Institute



Water Power Program

1950	1960	1970	1980	1990	2000	2007	2009	2010

Our core NW competencies enabled us to take on additional large national security challenges

Vertical-axis Wind Turbine

NRC cask certification studies & core melt studies

Solar Tower opens

Combustion Research Facility (CRF) opens to researchers

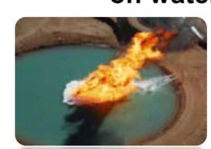
Distributed Energy Technology Laboratory (DETL) to integrate emerging energy technologies into new and existing electricity infrastructures

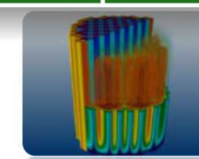
Power grid reliability study

SunCatcher™ partnership with Stirling Energy Systems

Sunshine to Petrol Pilot Test

Large-scale pool fire tests of liquefied natural gas (LNG) on water





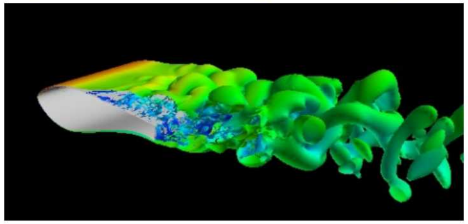
Consortium for Advanced Simulation of Light Water Reactors (CASL)

Climate study uncertainties to economies

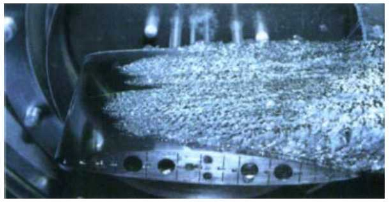
Combustion Research Computation and Visualization (CRCV) opens

Device Modeling/Testing

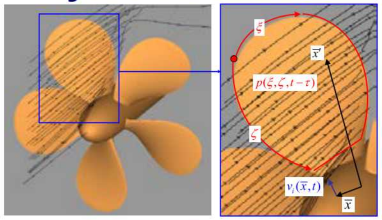
Hydrofoil Design/Analysis



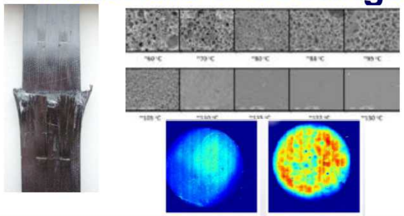
Cavitation



Hydro-Acoustics



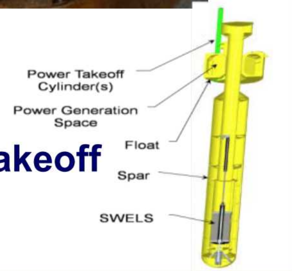
Materials & Coatings



Performance Modeling

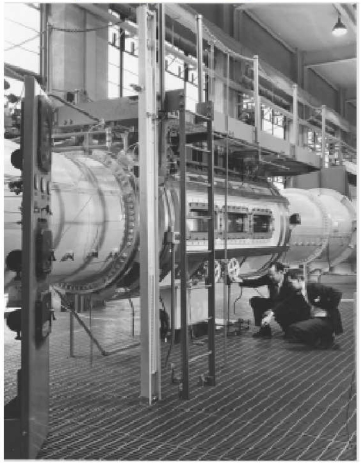
Rotor Design & Testing

Power Takeoff Testing



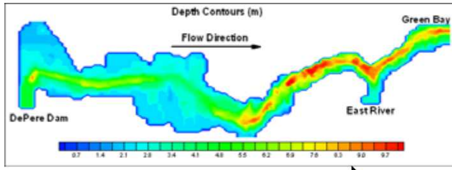
Columbia Power 1/15th Scale Test (OSU)

Water Tunnel (PSU/ARL)



Coupled Device-Array and Environmental Analysis

SNL-Delft3D-CEC



Components | Sub-systems | System Testing | Deployment

Class Goals

- Familiarize participants with the Delft3D modeling suite
  - Basics of Delft3D flow module (FLOW)
  - Grid generation (RGFGRID, QUICKIN)
- Describe current energy conversion (CEC) enhancement
  - ***SNL-Delft3D-CEC enhancement for turbine modeling***
- Develop hands-on experience with Delft3D example models
  - Straight channel and San Francisco Bay site examples
- Identify gaps/challenges for meeting CEC application/research goals
- Feedback on class structure and tools

Delft3D

Hydrodynamic and Environmental Evaluations

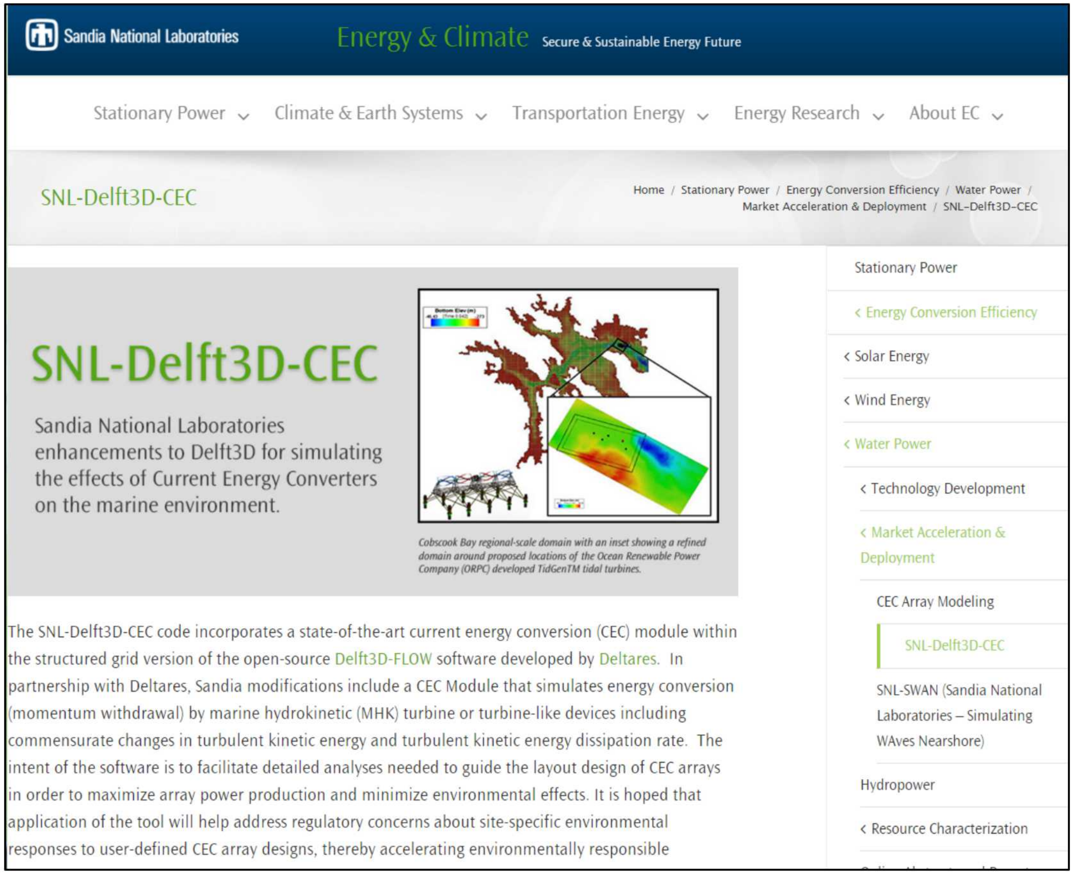
- **Description**
  - World leading 3D modeling suite to investigate hydrodynamics, sediment transport, morphology, and water quality for fluvial, estuarine, and coastal environments

- **Background**
  - **Delft3D FLOW, MOR, and WAVE are open source as of 2011**
  - A historically trusted code that is well respected and validated

https://oss.deltares.nl/web/delft3d/about

SNL-Delft3D-CEC Website

- **General software description**
  - Links to Deltares software and Delft3D
- **Link to source code (GitHub)**
  - https://github.com/SNL-WaterPower/SNL-Delft3D-CEC
- **Three self-guided tutorials**
  - Getting started
  - Straight channel model build
  - San Francisco Bay model build
  - Case Files for all builds



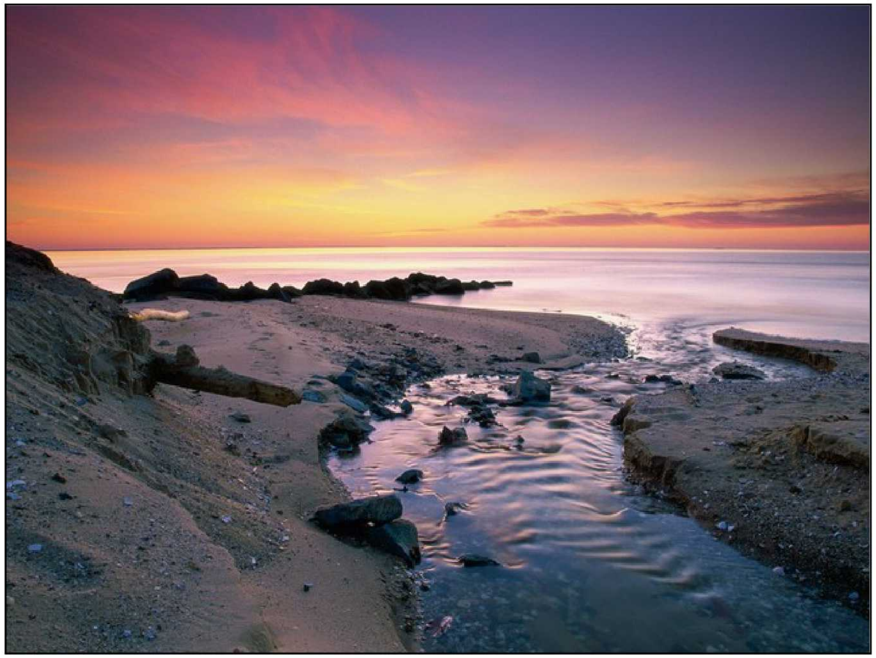
SNL-Delft3D-CEC

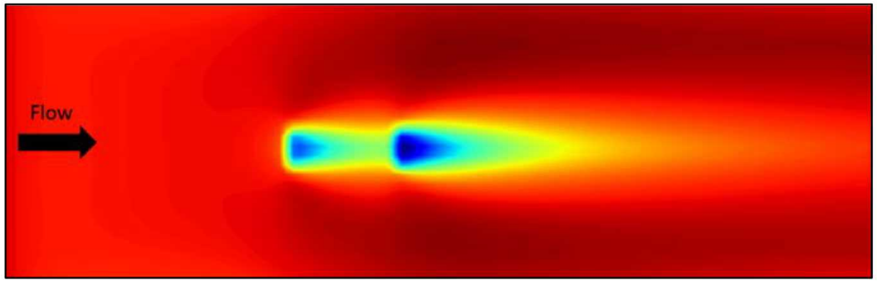
CEC Array Environmental Effects & Performance

- **Objectives**
  - Develop and demonstrate **SNL-Delft3D-CEC**: A tool for **balancing** CEC **efficiency** and **environmental effects**.
    - **Maximize power** and **minimize** potentially harmful **environmental effects**
  - Address **CEC array-power performance and environmental concerns** over large-scale development.

- **Background**
  - **High-fidelity CFD codes** (LES or URANS) are **computationally expensive** for large domains.
  - Some **lower fidelity CFD-RANS codes** incorporated vegetative resistance/losses, but were **not CEC specific.**
  - SNL developed the **Delft3D CEC Module** through DOE sponsorship.

- **Tool (Leverage Well-Respected Code)**
  - Delft3D–
    - Originally developed by Deltares, supported by SNL since 2015
    - Flexible mesh (CEC modeling not yet included)
    - Coupled-equation solution (mass, momentum, TKE…)
  - **CEC module** in addition to advanced **sediment dynamics**, and **water-quality** routines.



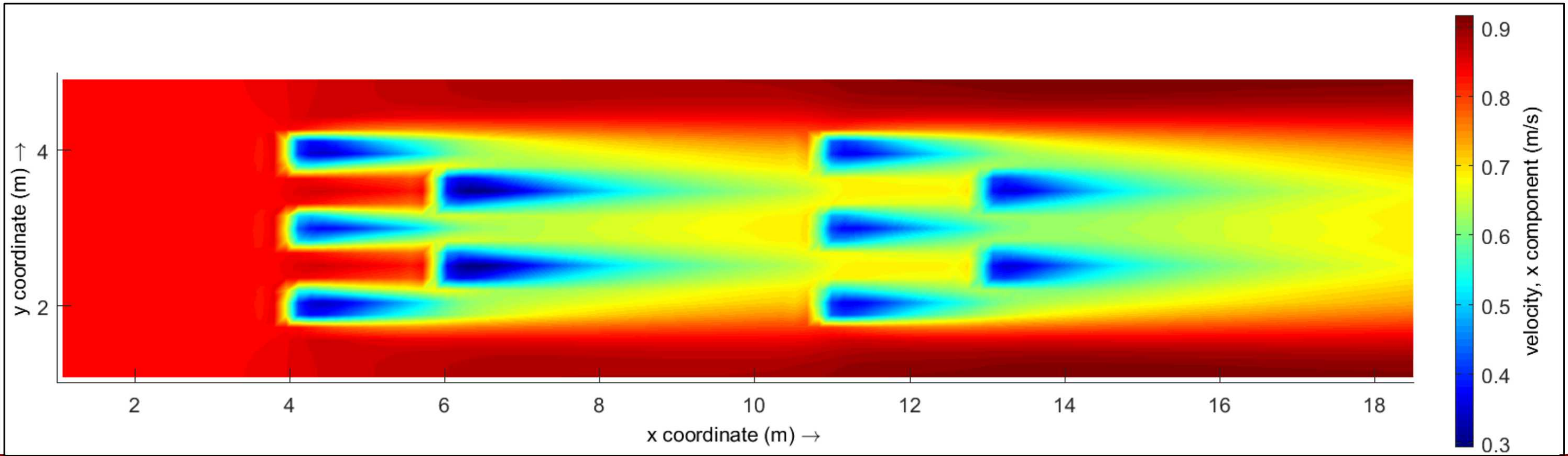


Current Energy Capture (CEC)

- Economic Concerns
  - Startup costs
  - Operation/maintenance costs
  - Power generation efficiency
  - Environmental impact
- Ecological Concerns
  - Water elevation/wake
  - Volumetric flow/tidal range
  - Sediment dynamics
  - Water quality

CEC Energy Absorption Module

- CEC device energy removal is manifest as:
  - Decreased momentum
  - Altered (usually increased) turbulent kinetic energy (TKE)
  - Increased turbulence dissipation rate (turbulent length scale)
- Momentum and K-ε are advected and dispersed downstream

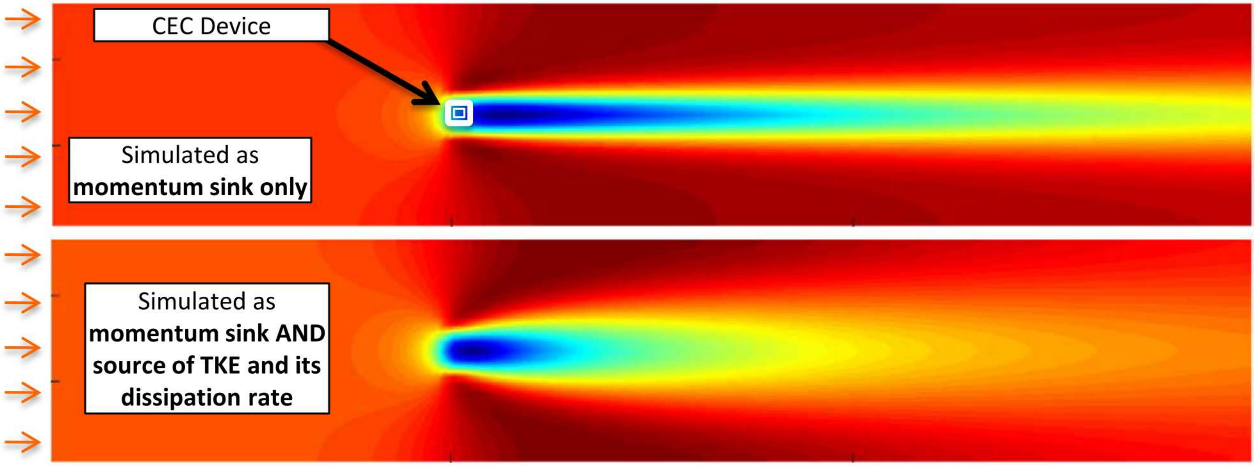


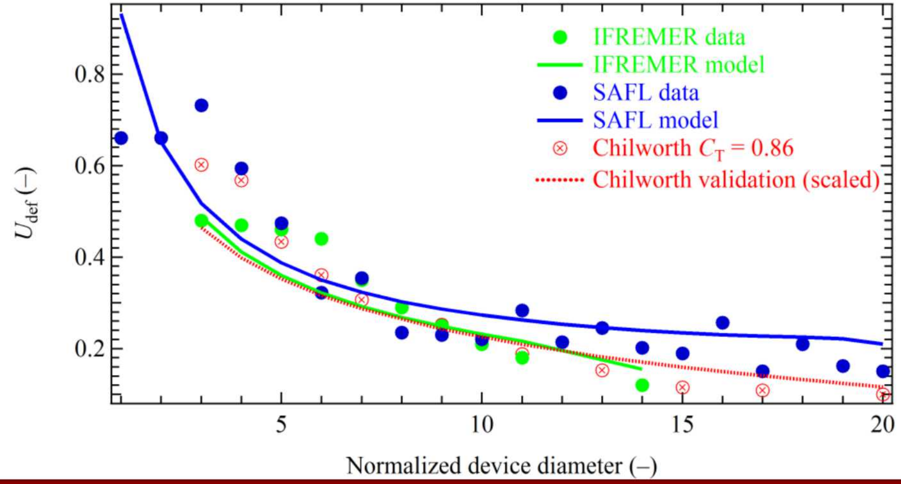
CEC Module Example: Single Device

- SNL-Delft3D-CEC simulates the effects of CEC-devices on flow
- Laboratory data sets (turbines and actuator disks)

SAFL

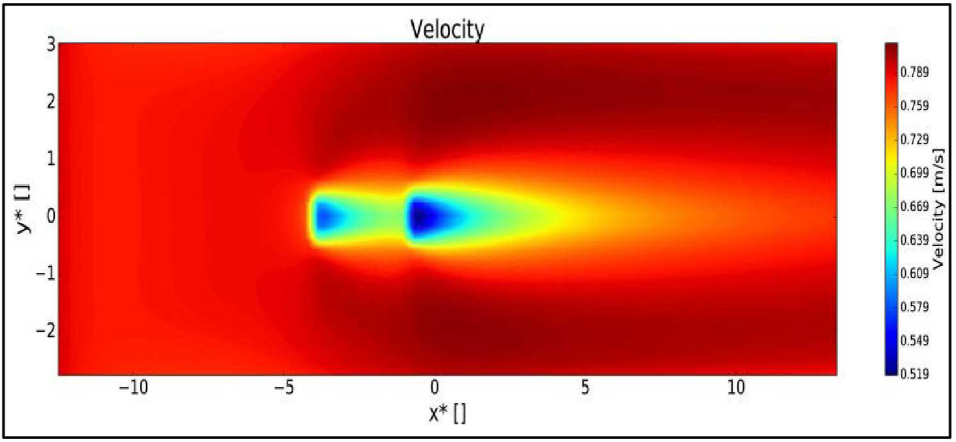
IFREMER

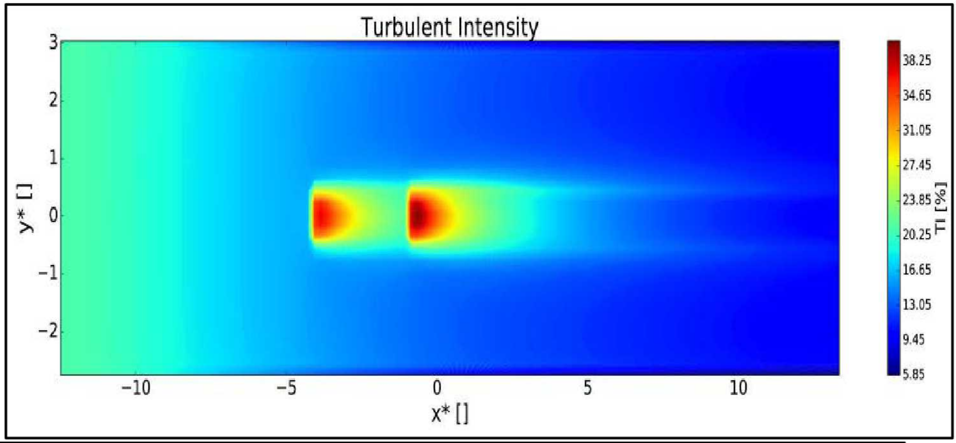


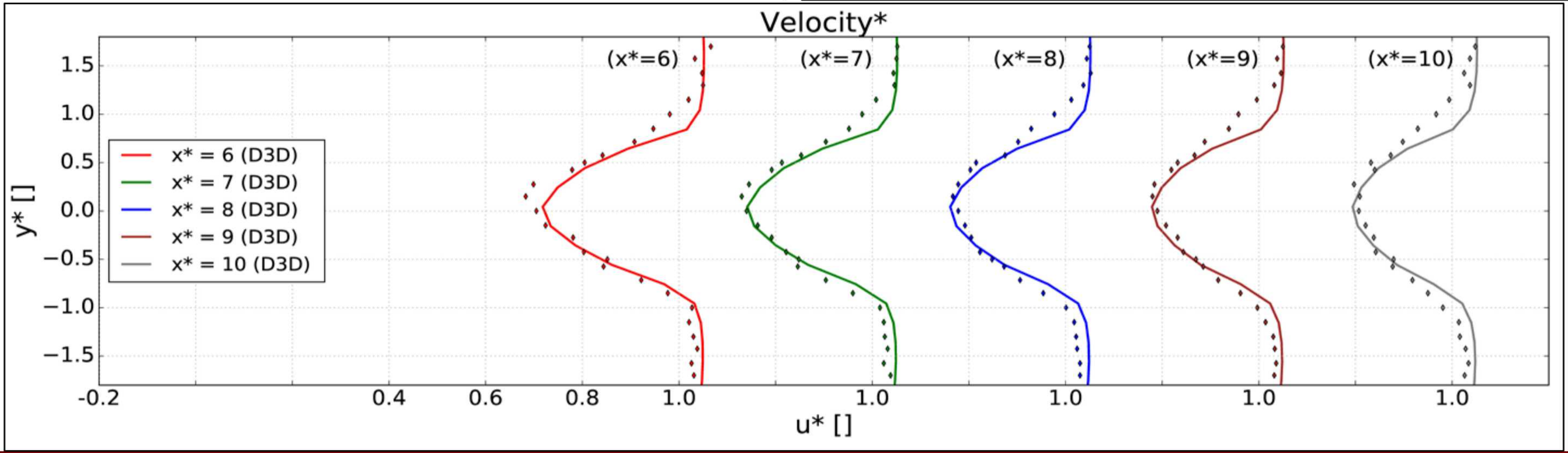


CEC Module Validation: Multiple Devices

- CEC series data set (Mycek et al., 2014) using scaled turbines
- Shear and wake interactions are observed and simulated







Example Site Model: San Francisco Bay

- Delft3D simulates flow for large sites
- San Francisco Bay bathymetry from USGS, 2012
- Movie: depth averaged velocity, duration = 2 days

https://sfbay.wr.usgs.gov/sediment/sfbay/downloads.html

http://energy.sandia.gov/snl-delft3d-cec/

San Francisco Bay: Georeferenced

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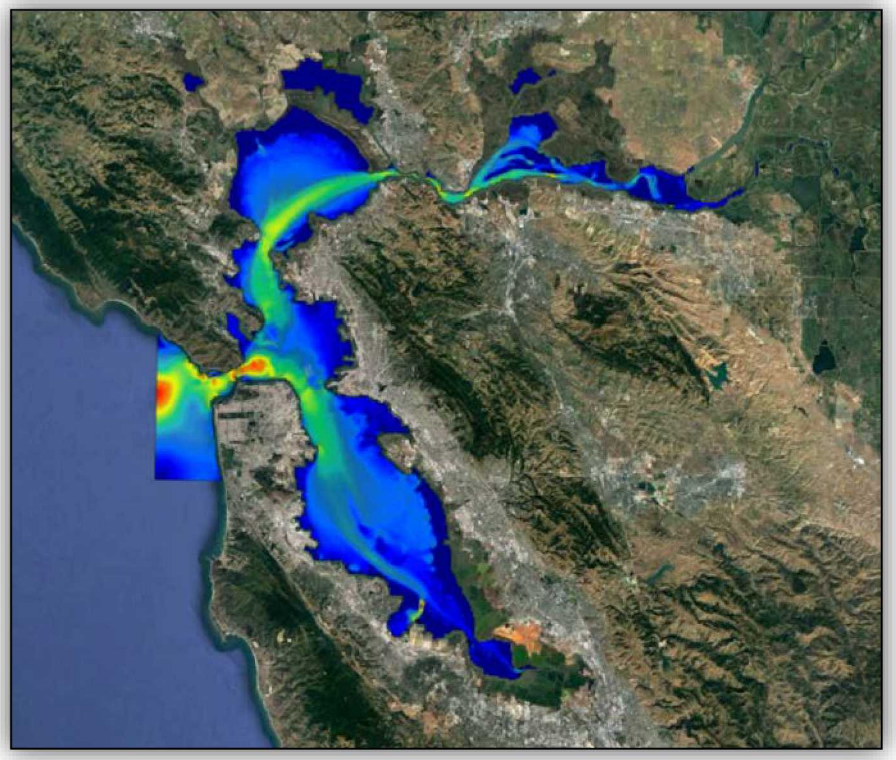
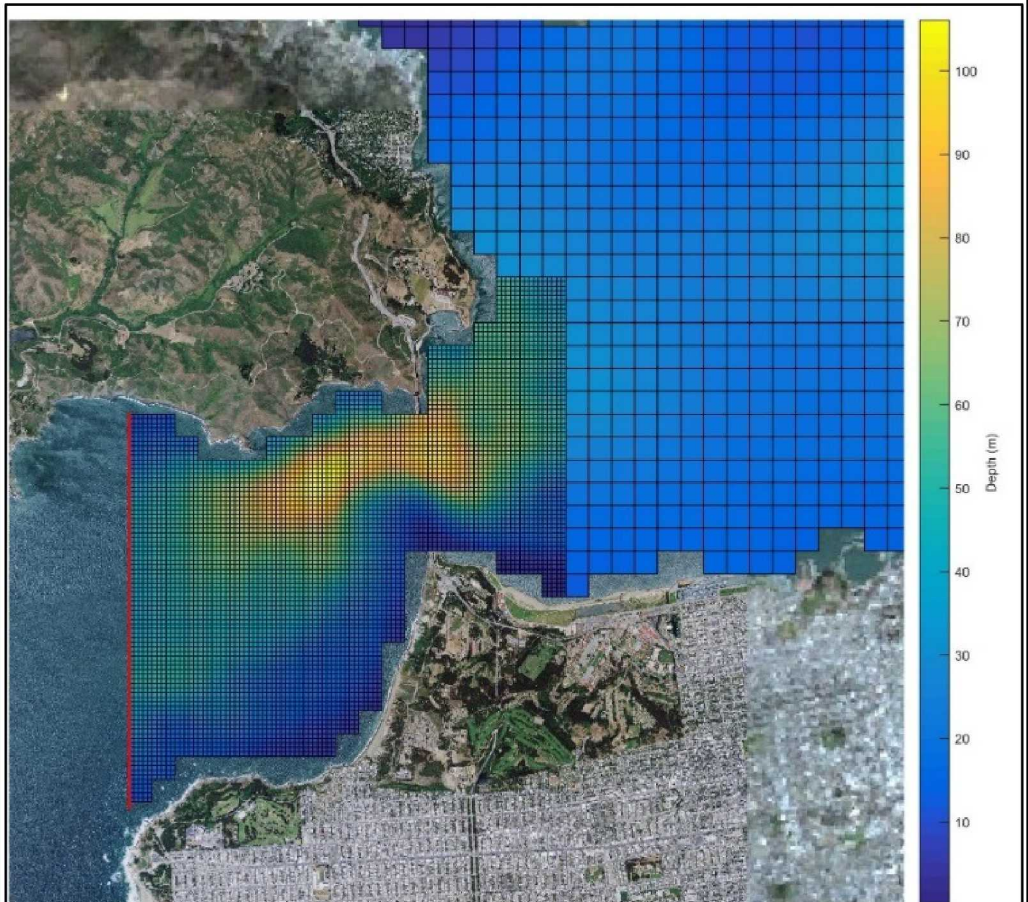
Depth

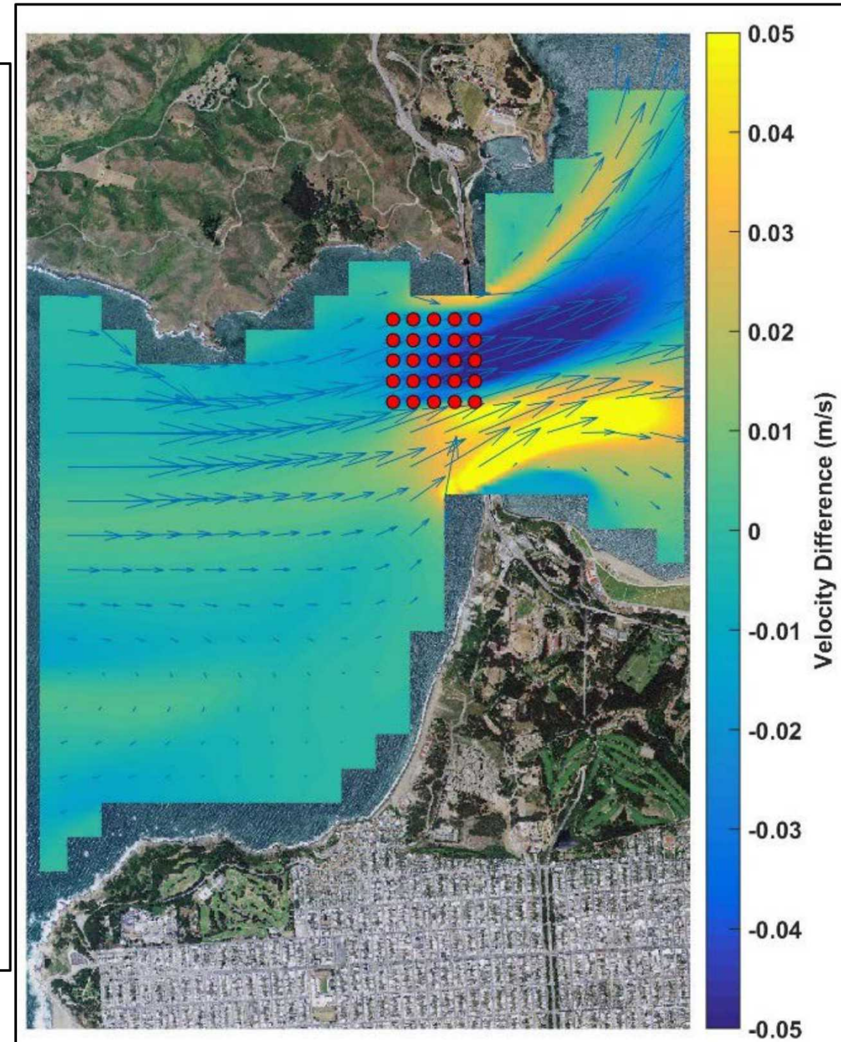
Depth-averaged Velocity



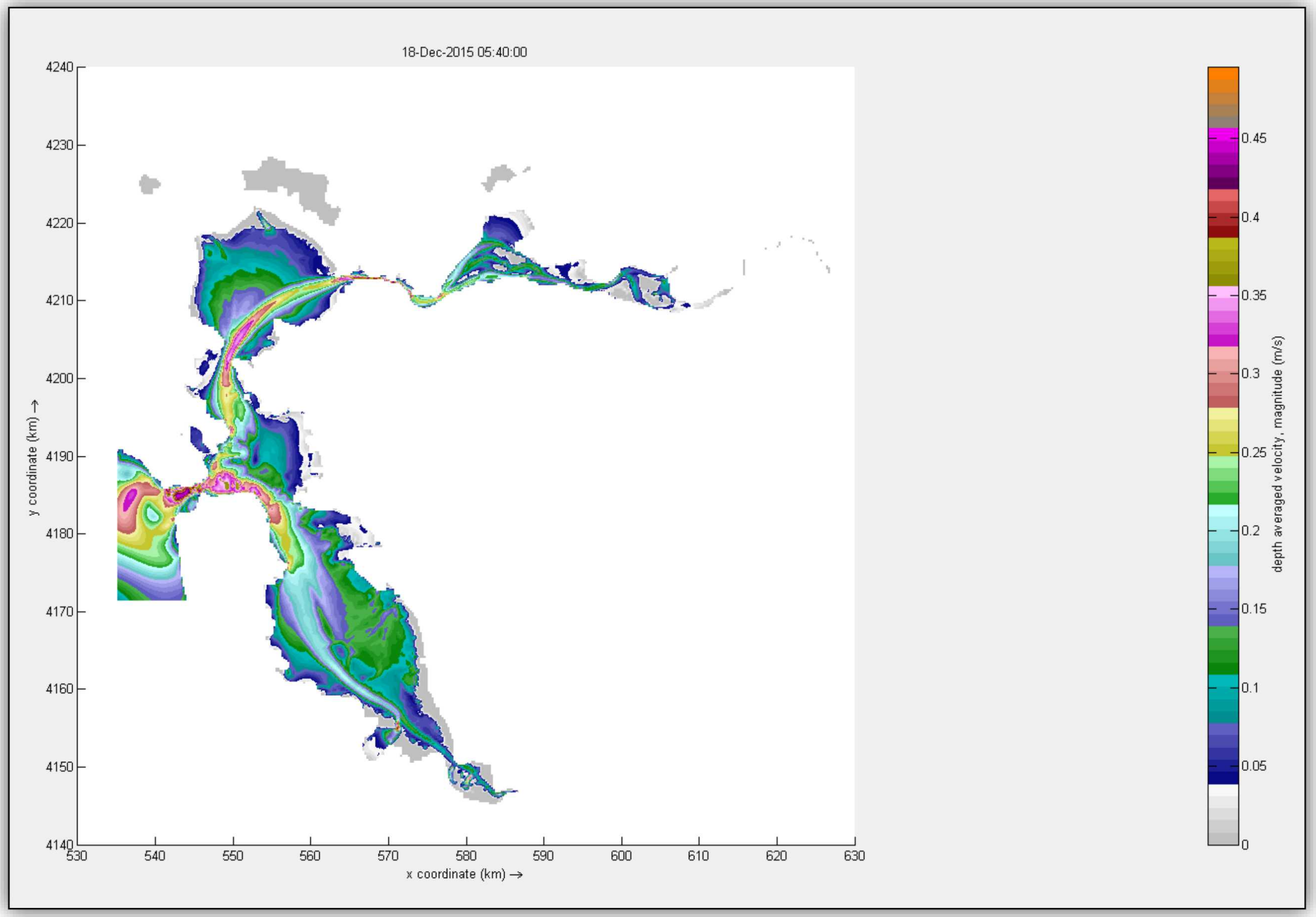
"San Francisco Bay" 37°51'25.60"N and 122°05'18.88 W. *Google Earth.*

San Francisco Bay Model





Now… On to the Training



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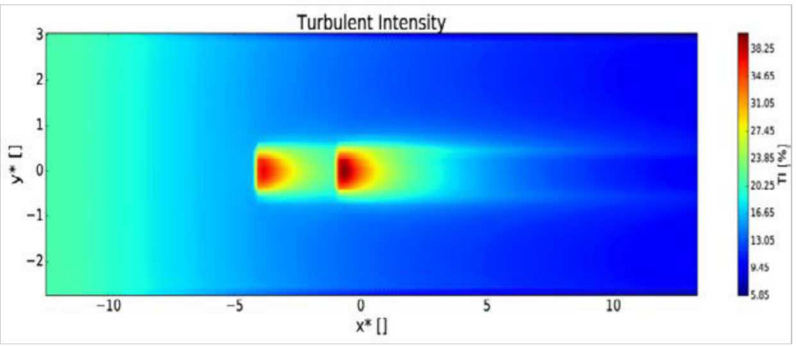

Delft3D FLOW: Hydrodynamic Model

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Water Power Program

U.S. DEPARTMENT OF ENERGY

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Outline

- Delft3D Development History.
- Delft3D Capabilities.
- Delft3D Flow Hydrodynamics.
- Transition to Sandia CEC Module (SNL-Deflt3D-CEC).

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Delft3D Software Suite

- Delft3D (FLOW, MOR, WAVE) is a public-domain surface-water modeling system incorporating fully integrated grid generation, hydrodynamics, waves, sediment dynamics, and water quality (all GUI driven).

- Delft3D can be used for 2D and 3D unsteady simulations of rivers, lakes, estuaries, and coastal regions.

Delft3D Development History

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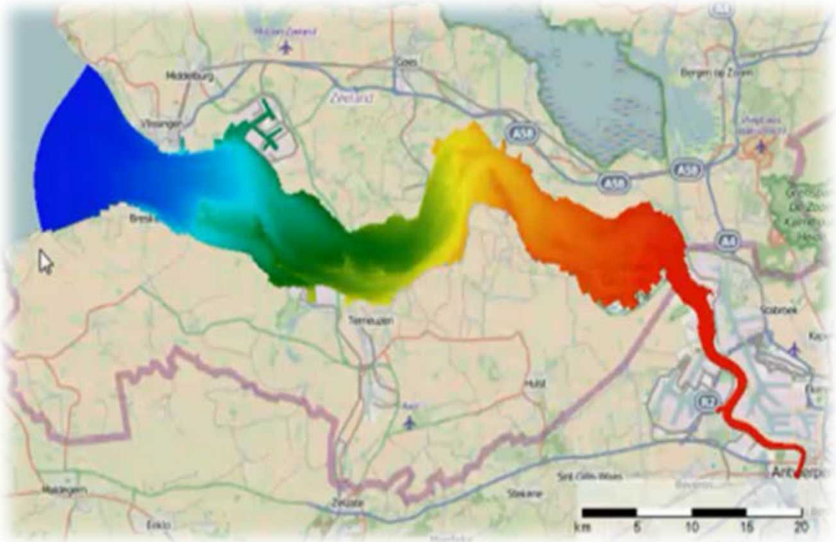
- Developed by Deltares, an independent institute for applied research in water resources in the Netherlands.
- Pubic-domain version was released in 2011 (flow, morphology, and waves modules).
- Currently used internationally: US, Netherlands, Hong Kong, Singapore, Australia, Venice, etc.

Sandia National Laboratories

Delft3D Capabilities

- Delft3D resolves circulation and transport in complex environments
  - Estuaries, rivers, lakes, and coastal waters
- Delft3D Simulates:
  - Scalar transport:
    - Dye-tracer
    - Temperature
    - Particles
    - Water-quality variables
  - Density stratification due to:
    - Salinity
    - Temperature
    - Sediment concentration



Courtesy of Deltares

Deltares
Enabling Delta Life

Delft3D Capabilities

- Directly coupled sediment and contaminant fate and transport models with multiple sub-model options.
- Simulates wetting and drying of flood plains, mud flats, and tidal marshes.
- Coupled morphology modeling.
- Coupled wave modeling.

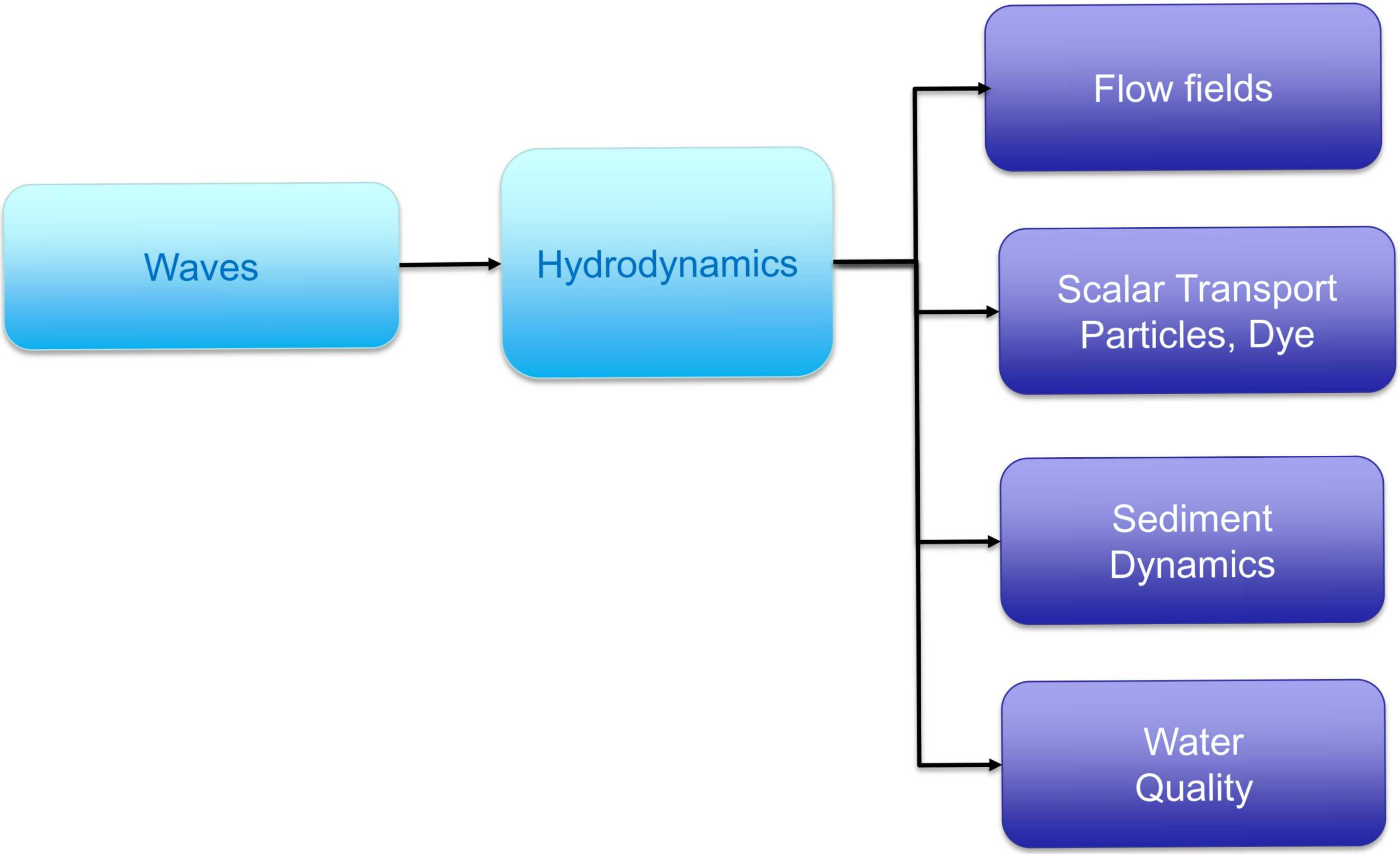
Delft3D Capabilities

- Simulates hydraulic control structures such as dams and culverts.
- Simulates wave boundary layers and wave-induced currents.
- Pre- and post-processing software through the Delft3D-GUI.

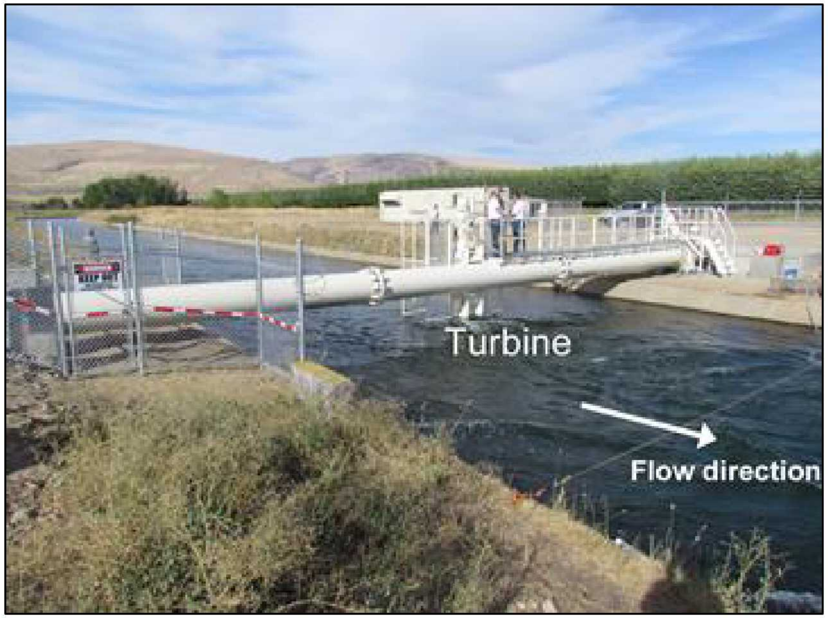
Example of Peer-Reviewed Delft3D Applications

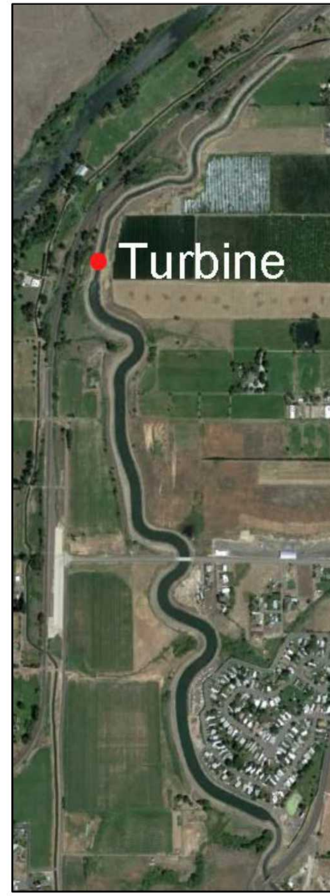
- Rivers – Allier River (FR), Rhine River (DEU), Yellow River (CH), Pearl River (MS), East River (NY).
- Lakes – Lake Markermeer (NL), Lake Geneva (SW), El-Burullus Lake (EGP), Lake Marken (NL), Taihu Lake (CH), Poyang Lake (CH), Eastern Lake Ontario (CAN), Lake Eğirdir (TRK), Lake Baikal (RUS).
- Estuaries – Rhine Delta (DEU), Mossy Delta (CAN), Scheldt River Basin (BEL), Patuxent River (VA), Teign Estuary (UK).
- Coastal – Egmond (NL), Hong Kong (CH), Maasmond Area (NL), Coastal Carolina (NC), Dutch Coast (NL), Wadden Sea (NL).

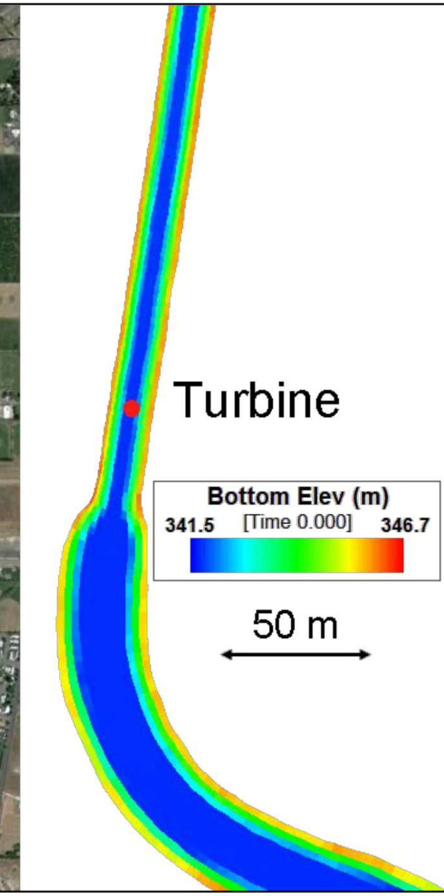
Basic Delft3D Structure

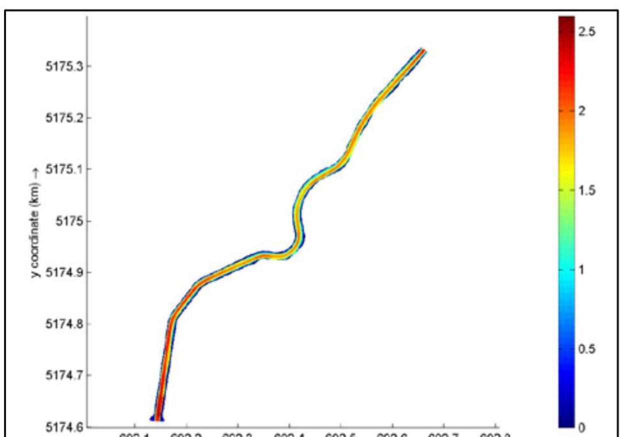


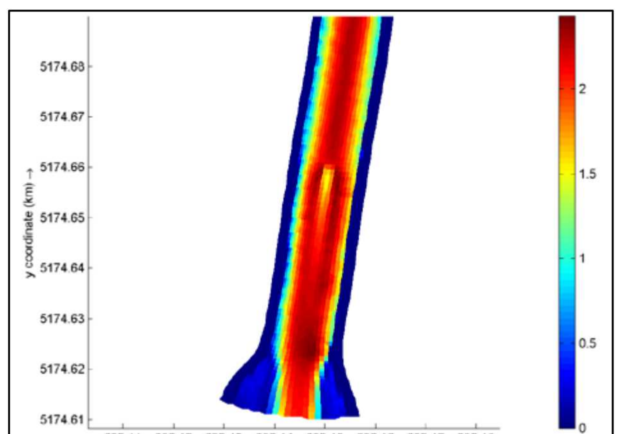
Channel Flow

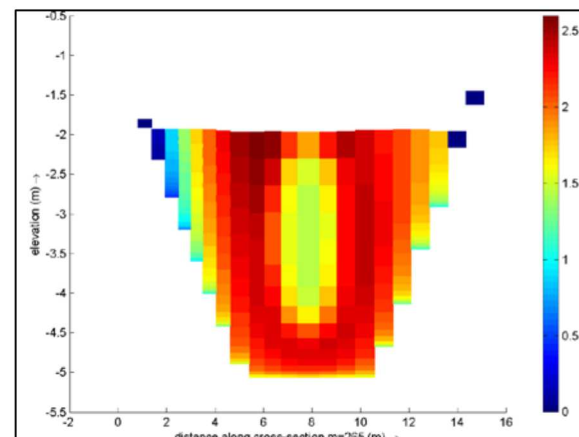






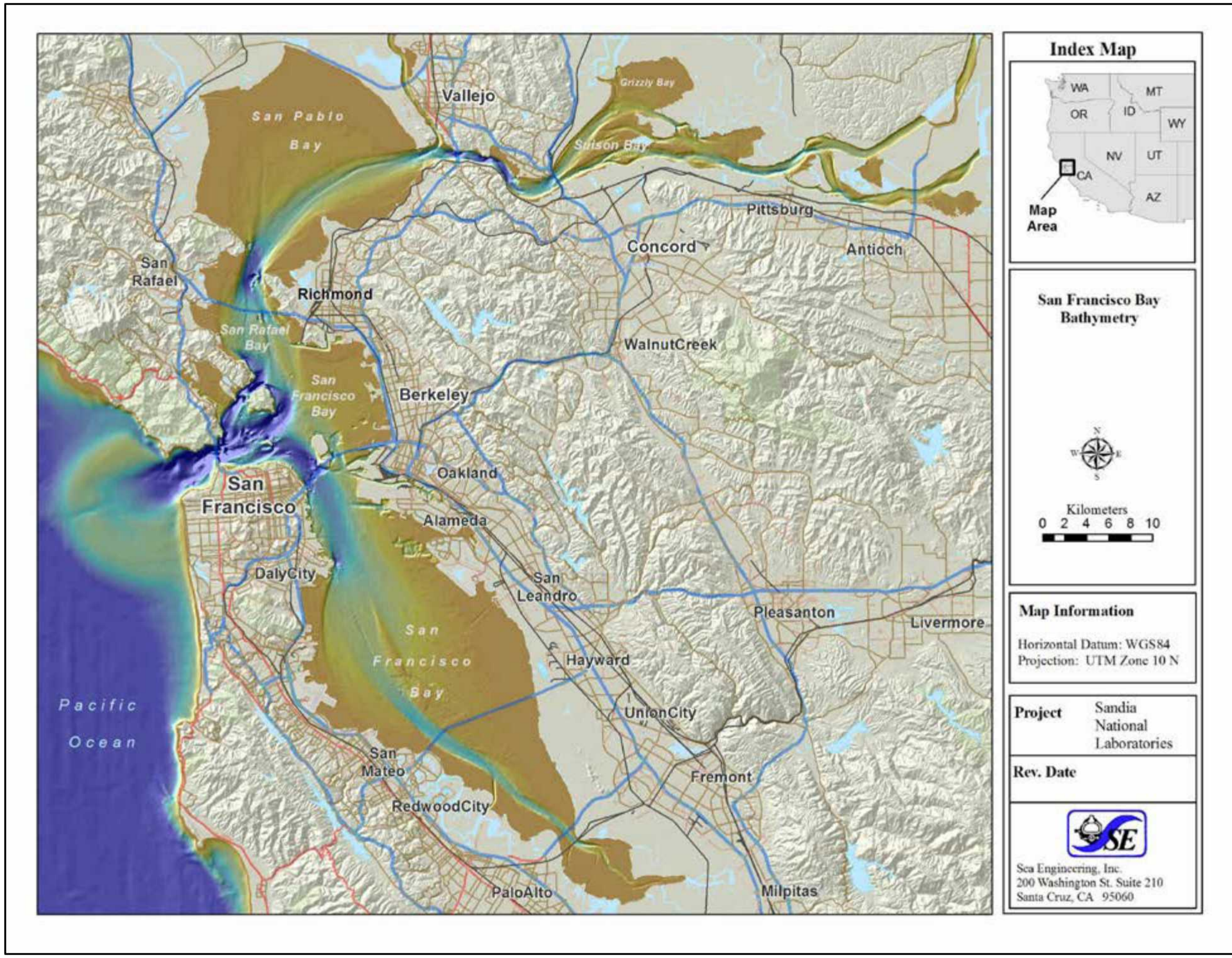




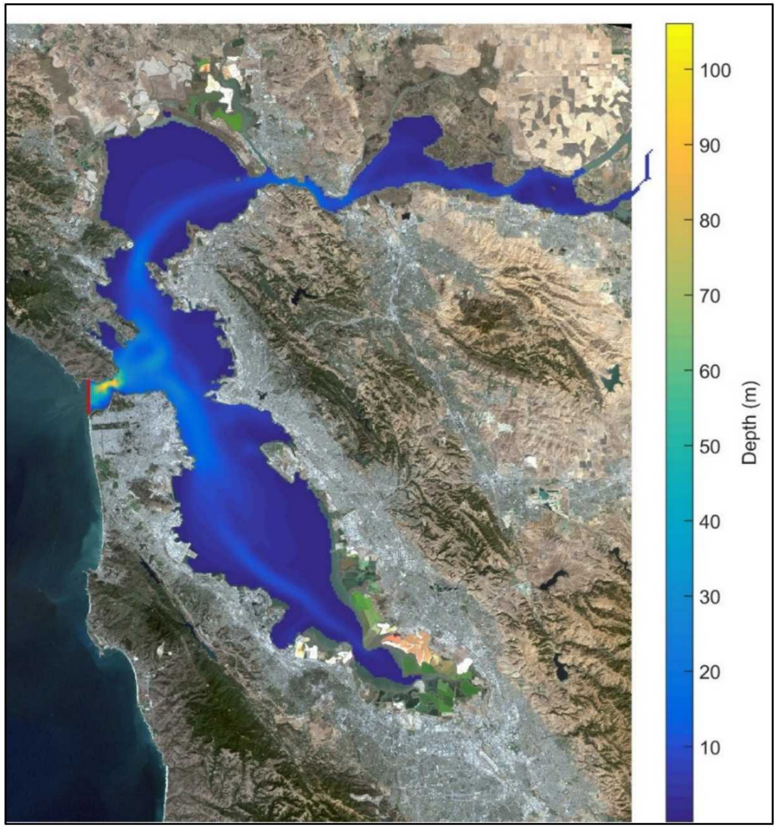


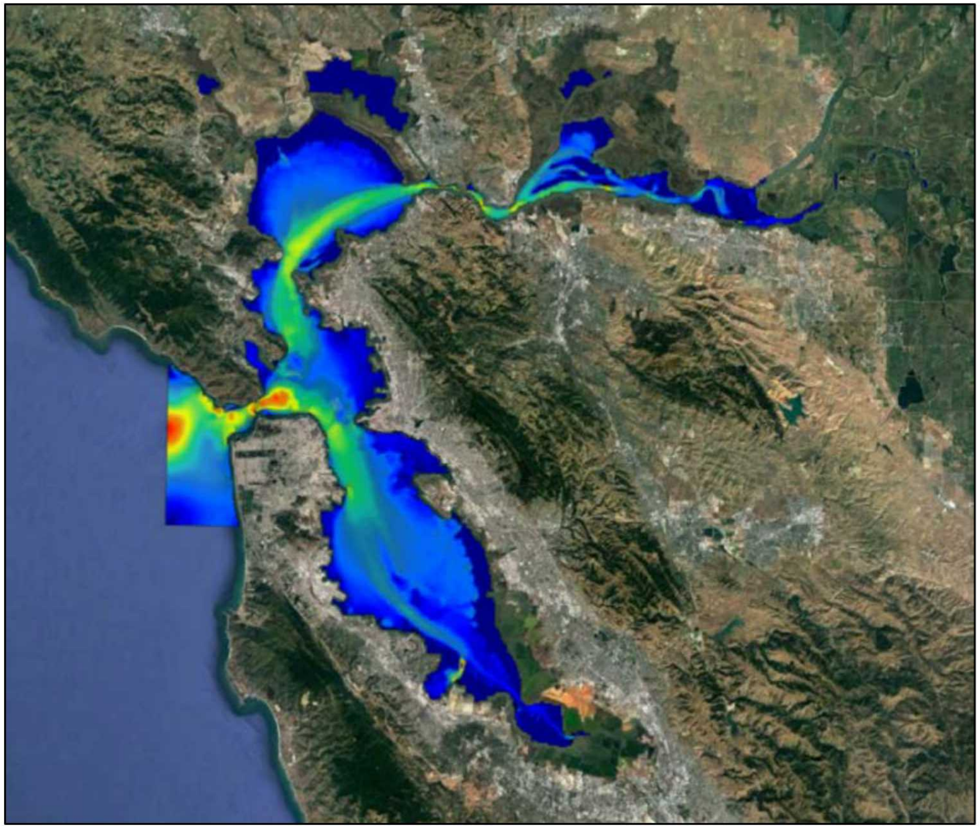
San Francisco Bay

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



San Francisco Bay

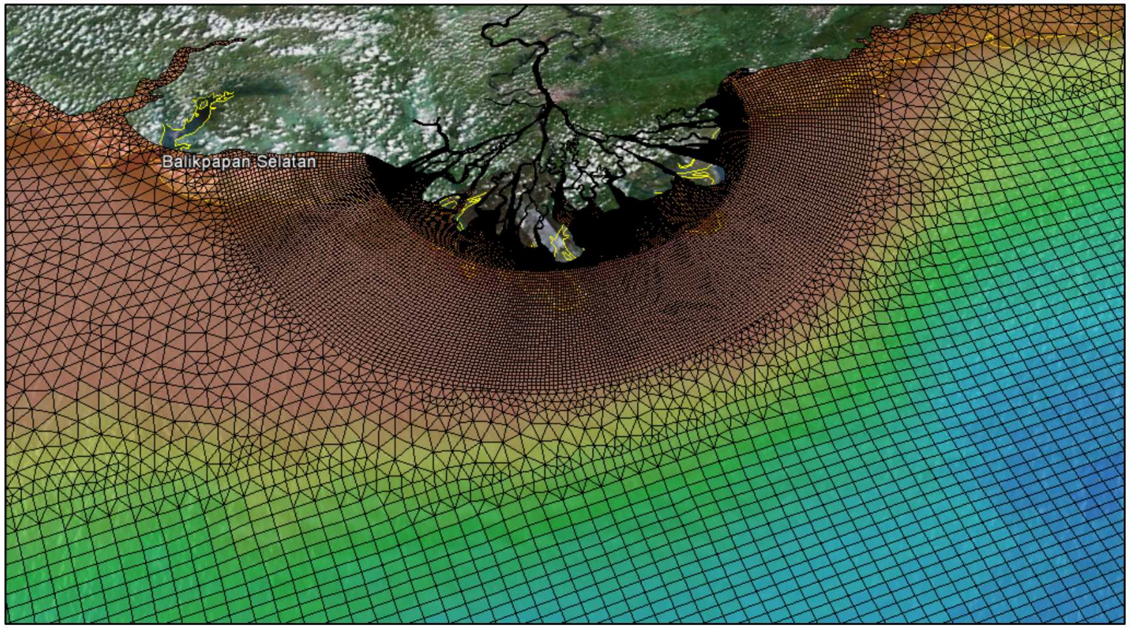




With accurate boundary conditions, a well calibrated model reproduces the hydrodynamics of the system.

Flexible Grids (CEC in progress)

Unstructured grids can be used to more accurately represent systems.

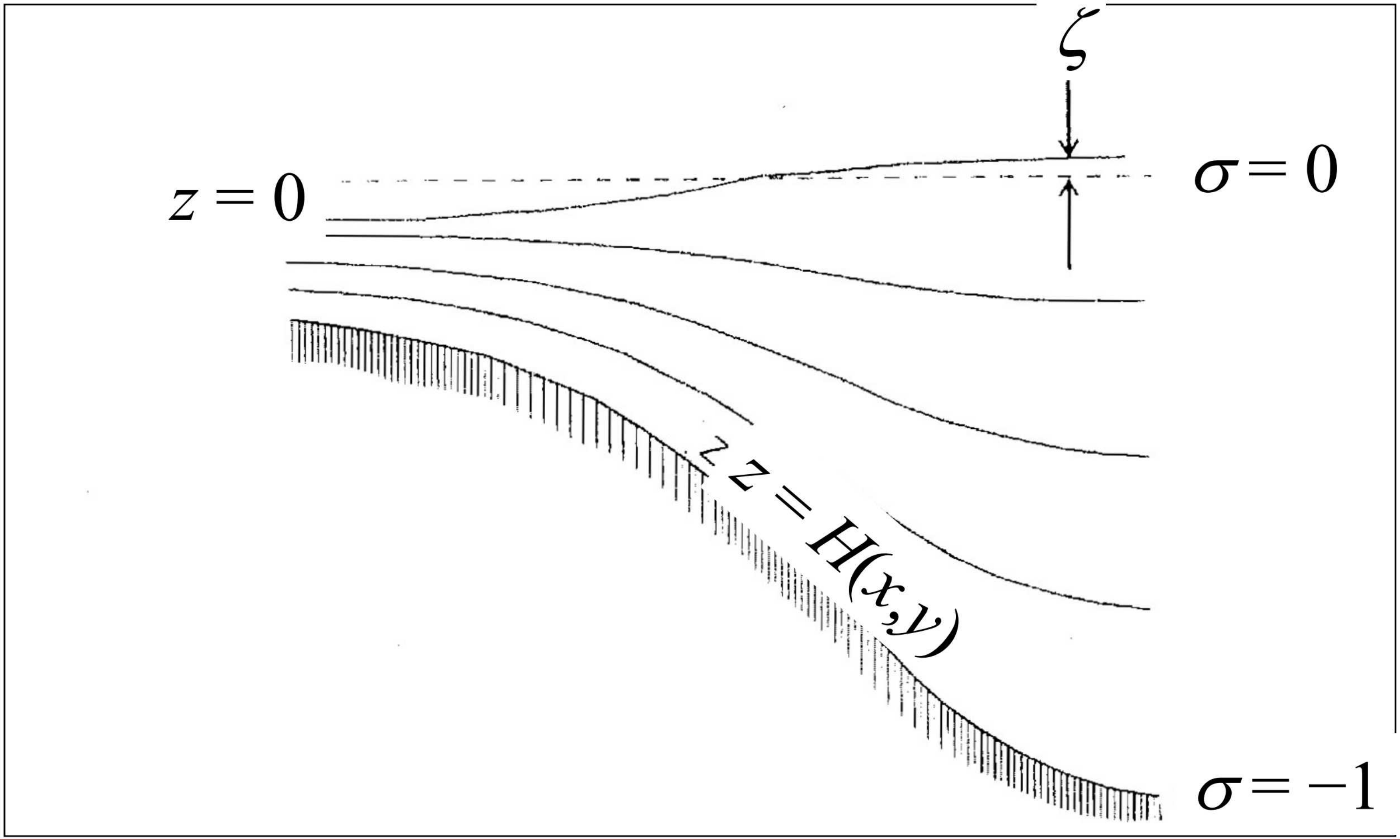


Delft3D Hydrodynamic Module

- Fully 3D, with 2D options.
- Mesh type: Boundary-fitted curvilinear, Cartesian, or flexible.
- σ-level or stretched bathymetry-following grid in the vertical or *Z*-grid.
- Includes an algebraic turbulence model, *k-L*, k-ε or, LES turbulence options.
- Alternating-direction implicit flow solution.

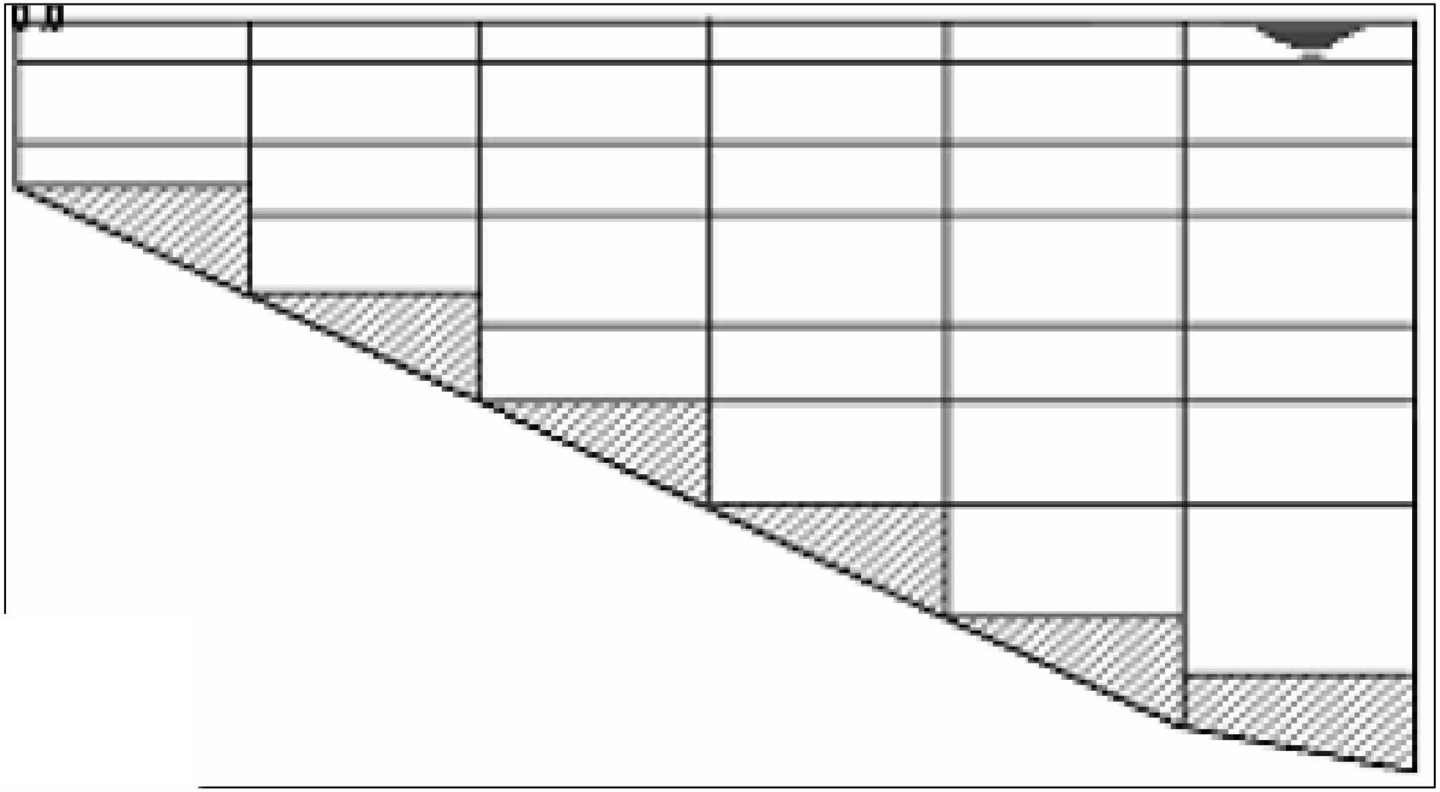
Delft3D Hydrodynamic Module - Vertical

In Delft3D, the sigma (σ or stretched) transformation is used to develop a “bottom following” grid.



Delft3D Hydrodynamic Module - Vertical

In Delft3D, a *Z*-grid is also available. This is appropriate when simulating horizontal density interfaces (*isopycnals*) in regions with steep bottom slopes.



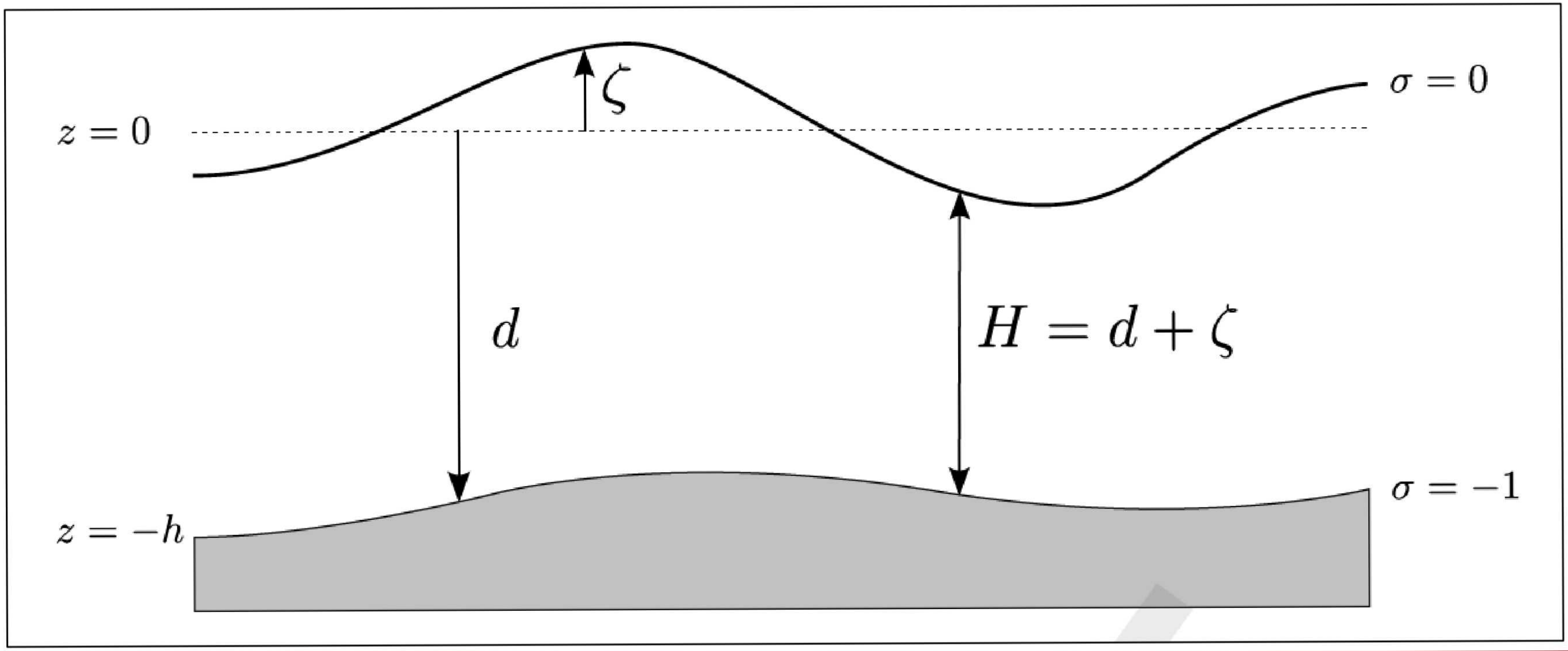
$$z = \zeta$$

$$z = -H(x,y)$$

Delft3D Hydrodynamic Module - Vertical

The σ coordinate is defined as:

$$\sigma = \frac{z - \zeta}{d + \zeta} = \frac{z - \zeta}{H}$$



Delft3D Physical Phenomena

Sandia National Laboratories

- Free-surface gradients (barotropic effects).
- Coriolis forces.
- Density gradients (equations of state).
- Horizontal pressure density gradients (baroclinic effects).
- Turbulence-induced mass and momentum fluxes.
- Tidal forcing at open boundaries.
- Spatiotemporal wind shear stresses, including cyclones.
- Spatiotemporal atmospheric pressure at the water surface.
- Spatially varying bottom stresses.
- Time-varying sources/sinks (e.g., river discharges).

Delft3D Physical Phenomena

- Drying and flooding of tidal flats.
- Heat exchange through the free surface.
- Evaporation and precipitation.
- Tide-generating forces.
- Effects of secondary flows on depth-averaged momentum equations.
- Lateral shear stresses at walls.
- Vertical exchange of momentum due to internal waves.
- Influence of waves on bed shear stress.
- Wave-induced (radiation) stresses and mass fluxes.
- Flow through hydraulic structures.
- Transport of salt, heat, and other scalars.

Delft3D Atmospheric Forcing

- Wind stresses (including tropical cyclones) can drive fluid motion (mixing and transport).
- Atmospheric pressure affects water-surface elevation.
- Atmospheric coupling drives heat exchange:
  - Convective heat exchange (sensible)
  - Net incident solar short-wave radiation considering cloud cover (incoming and reflected)
  - Net incident atmospheric (long-wave) radiation (incoming and reflected)
  - Evaporative cooling (forced and free latent heat)

Delft3D Hydrodynamic Module

- **Three-dimensional continuity (Cartesian):**

$$H = d + \zeta$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (HU)}{\partial x} + \frac{\partial (HV)}{\partial y} = HQ$$

Discharge or withdrawal by precipitation or evaporation

$$Q = \int_{-1}^{0} (q_{\text{in}} - q_{\text{out}}) \mathrm{d}\sigma + P - E$$

- **With *U* and *V* the depth-averaged velocities:**

$$U = \frac{1}{H} \int_{d}^{\zeta} u \mathrm{d}z = \int_{-1}^{0} u \mathrm{d}\sigma$$

$$V = \frac{1}{H} \int_{d}^{\zeta} v \mathrm{d}z = \int_{-1}^{0} v \mathrm{d}\sigma$$

Delft3D Hydrodynamic Module

Conservation of momentum - *x* component (Cartesian):

Accumulation, Advection, Coriolis

$$\frac{\partial u}{\partial t} + \frac{u\partial u}{\partial x} + \frac{v\partial u}{\partial y} + \frac{w}{H}\frac{\partial u}{\partial \sigma} - fv =$$

Vertical eddy viscosity

$$-\frac{1}{\rho_0}P_x + F_x + \frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(\nu_V \frac{\partial u}{\partial \sigma}\right) + M_x$$

Pressure gradient, Horizontal Reynolds stress, Vertical momentum diffusion, External momentum source

Delft3D Hydrodynamic Module

- **Vertical velocity, *w*, in the σ-coordinate system is computed from the continuity equation (Cartesian):**

Accumulation — Advection — Source/sink

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} + \frac{\partial w}{\partial \sigma} = H\left(q_{\text{in}} - q_{\text{out}}\right)$$

Delft3D Hydrodynamic Module

- **The "physical" vertical velocity, *w*, in the Cartesian coordinate system are not involved in the model equations, but are calculated in post-processing:**

$$w = \omega_\sigma + \left[u\left(\sigma \frac{\partial H}{\partial x} + \frac{\partial \zeta}{\partial x} \right) + v\left(\sigma \frac{\partial H}{\partial y} + \frac{\partial \zeta}{\partial y} \right) \right] + \left(\sigma \frac{\partial H}{\partial t} + \frac{\partial \zeta}{\partial t} \right)$$

- **Where ω_σ is the velocity at iso σ-surfaces associated with upwelling or downwelling motions.**

Hydrostatic Pressure Assumption

- **Vertical accelerations due to buoyancy effects and sudden variations in bottom topography are neglected:**

$$\frac{\partial P}{\partial \sigma} = -g\rho H$$

- **After integration, the hydrostatic pressure is:**

$$P = P_{atm} + gH\int_{\sigma}^{0} \rho(x, y, \sigma', t)\,\mathrm{d}\sigma'$$

Hydrostatic Pressure Assumption

- **For constant water density and atmospheric pressure:**

$$\frac{1}{\rho_0} P_x = g \frac{\partial \zeta}{\partial x} + \frac{1}{\rho_0} \frac{\partial P_{\text{atm}}}{\partial x}$$

$$\frac{1}{\rho_0} P_y = g \frac{\partial \zeta}{\partial y} + \frac{1}{\rho_0} \frac{\partial P_{\text{atm}}}{\partial y}$$

Hydrostatic Pressure Assumption

- **For variable water density due to temperature and salinity gradients:**

Barotropic | Baroclinic

$$\frac{1}{\rho_0}P_x = g\frac{\partial \zeta}{\partial x} + g\frac{H}{\rho_0}\int_{\sigma}^{0}\left(\frac{\partial \rho}{\partial x} + \frac{\partial \rho}{\partial \sigma'}\frac{\partial \sigma'}{\partial x}\right)\mathrm{d}\sigma'$$

$$\frac{1}{\rho_0}P_y = g\frac{\partial \zeta}{\partial y} + g\frac{H}{\rho_0}\int_{\sigma}^{0}\left(\frac{\partial \rho}{\partial y} + \frac{\partial \rho}{\partial \sigma'}\frac{\partial \sigma'}{\partial y}\right)\mathrm{d}\sigma'$$

Delft3D Hydrodynamic Module

- Pressure changes due to floating structures are allowed.
- Rigid-lid computations are allowed.
- Reynolds stresses include the product of:
  - (flow) × (spatially variable eddy viscosity) × (corresponding components of the mean rate-of-deformation tensor)
    - These differ between 2D and 3D.

Delft3D Horizontal/Vertical Mixing

- For 3D, the horizontal eddy viscosity coefficient, $\nu_H \gg \nu_V$, is the superposition of:
  1. Sub-grid scale (SGS) turbulence, ν_{SGS}.
  2. 3D turbulence, ν_V.
  3. Reynolds-averaged shallow-water equations, $\nu_H^{\mathrm{background}}$.

$$\nu_H = \nu_{\mathrm{SGS}} + \nu_V + \nu_H^{\mathrm{background}}$$

- Vertical mixing is the sum of:
  1. Water kinematic viscosity, ν_{mol}
  2. The greater of the computed mixing coefficient from the 3D turbulence-closure model or the spatiotemporal user-defined ambient or "background" mixing.

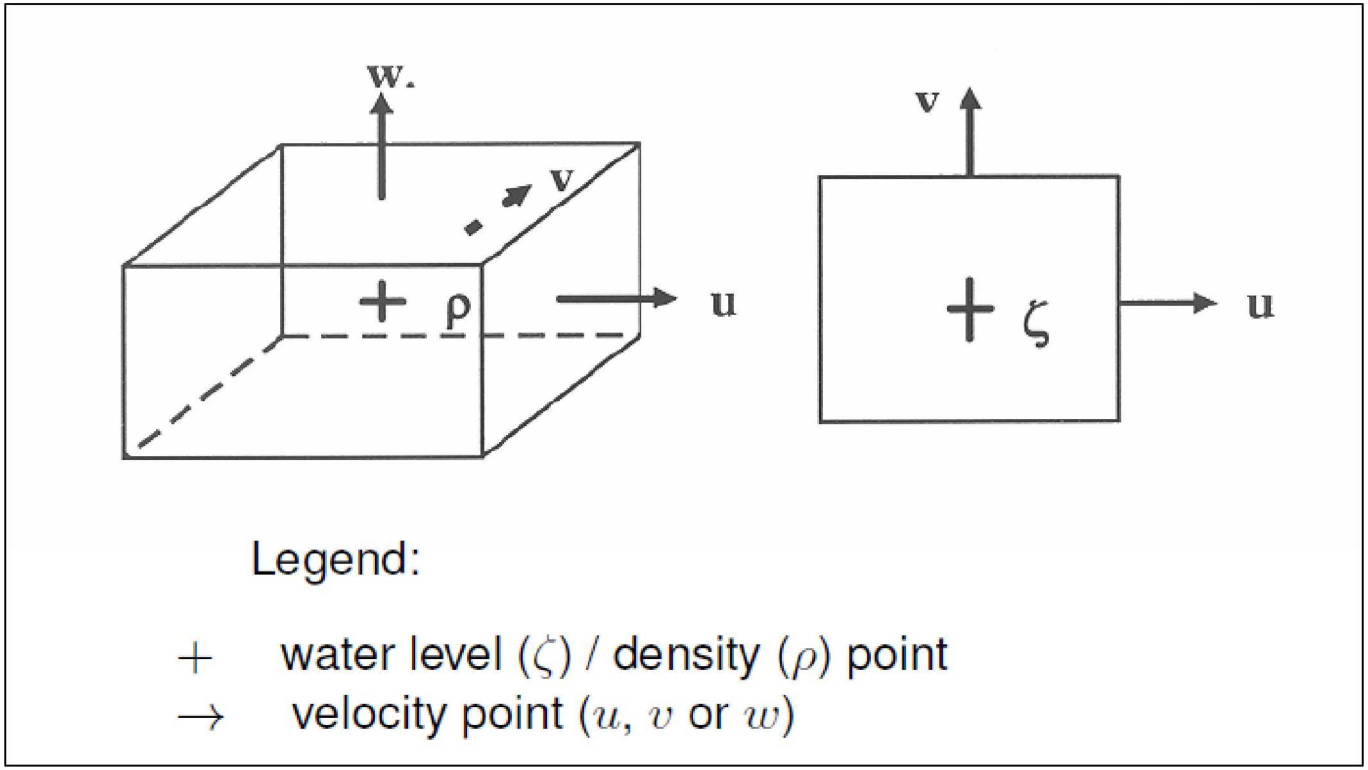
$$\nu_V = \nu_{\mathrm{mol}} + \max\left(\nu_{\mathrm{3D}}, \nu_V^{\mathrm{background}}\right)$$

Delft3D Turbulence Options

- Because turbulence processes are "sub-grid" scale, the primitive variables are space and time averaged and require *appropriate closure assumptions.*
- Four turbulence-closure models are available to determine the vertical eddy viscosity (ν_V) and vertical eddy diffusivity coefficient (D_V):
  1. Constant coefficient (user defined).
  2. Algebraic Eddy viscosity closure Model (AEM).
  3. *k-L* turbulence closure model.
  4. *k-ε* turbulence closure model (3D only).
- Each model calculates the turbulent kinetic energy (*k*), and its dissipation rate (ε) or mixing length (*L*) differently

Delft3D-FLOW Solution Scheme

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



Delft3D-FLOW Solution Scheme

- For computational efficiency, the solution of the transport equations uses a *mode-splitting* technique common in oceanographic models.

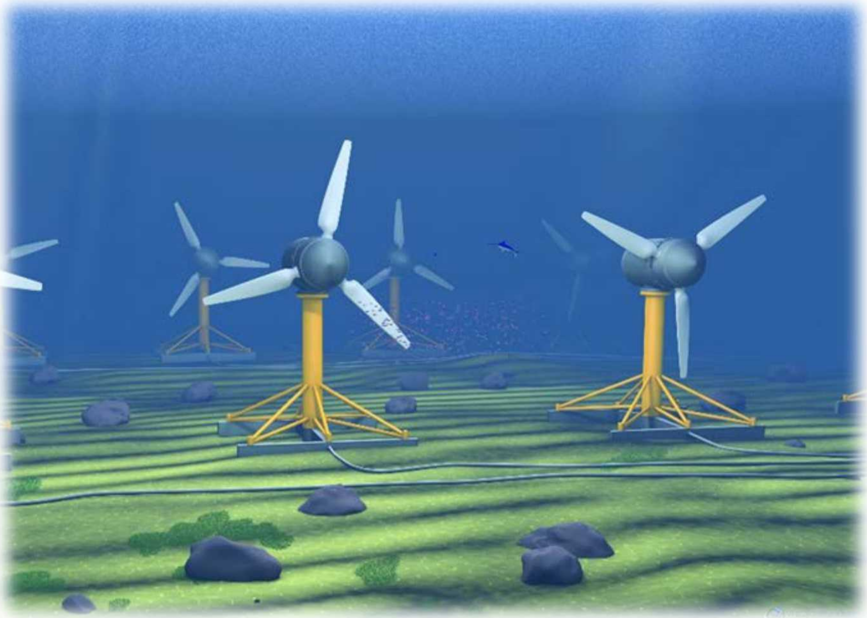
- The theory is based on the difference in movement of fast-moving external gravity waves and slower moving internal waves in a system.

- 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 (solved on a column of water).
    - 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 (solved across model sigma layers).

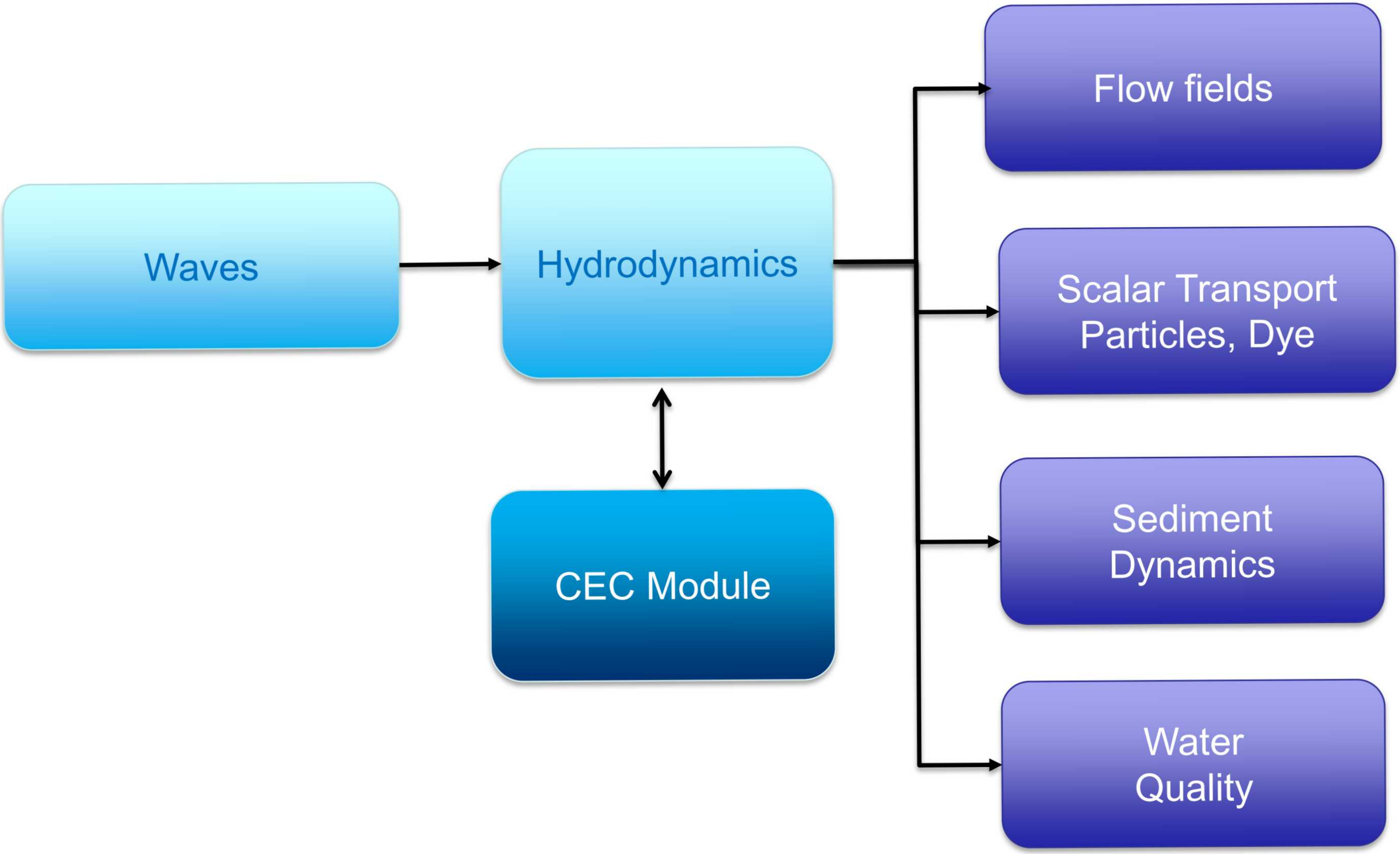
- The mode-splitting technique provides a robust and efficient solution for the hydrodynamics.

SNL-Delft3D-CEC

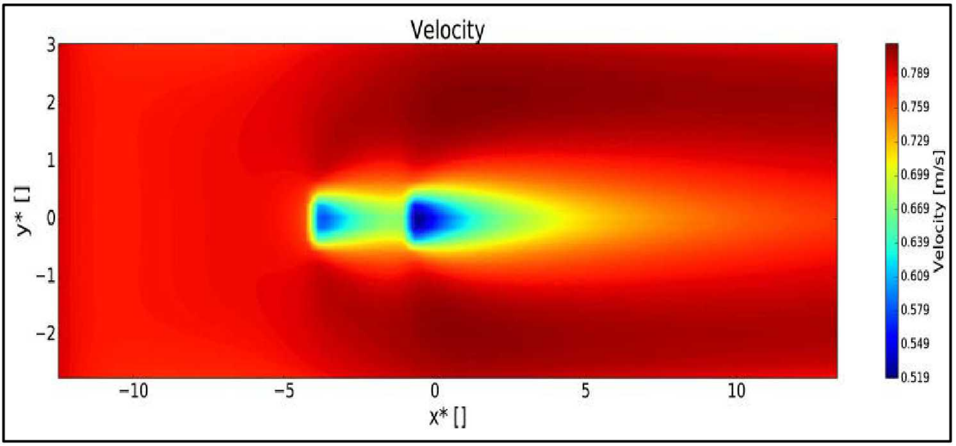
- SNL-Delft3D-CEC is an upgrade of Delft3D for predicting the effects of current-energy-capture (CEC) devices.

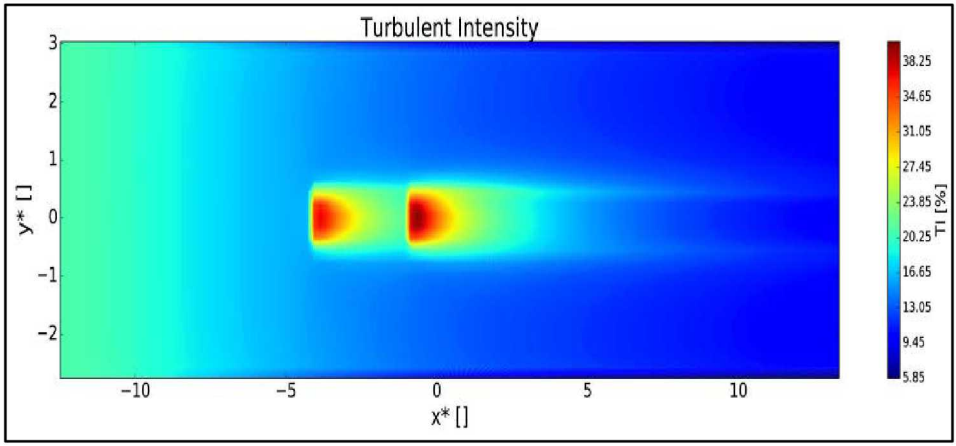


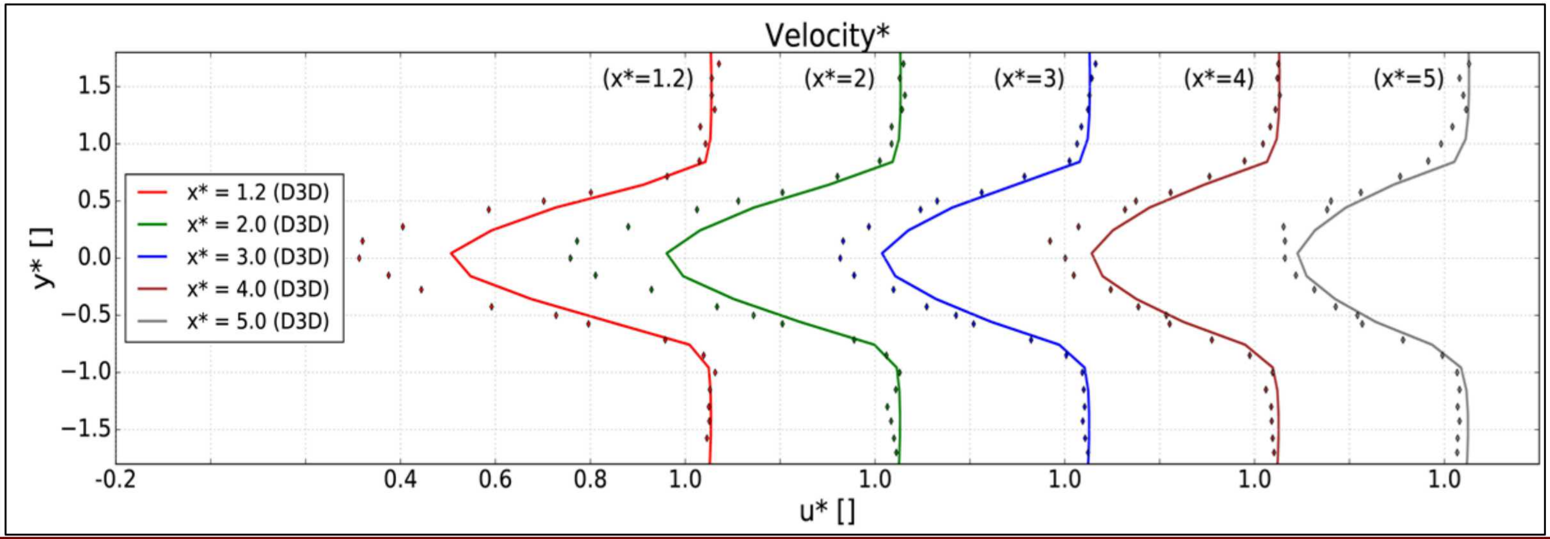
Basic Delft3D Structure



CEC Modeling







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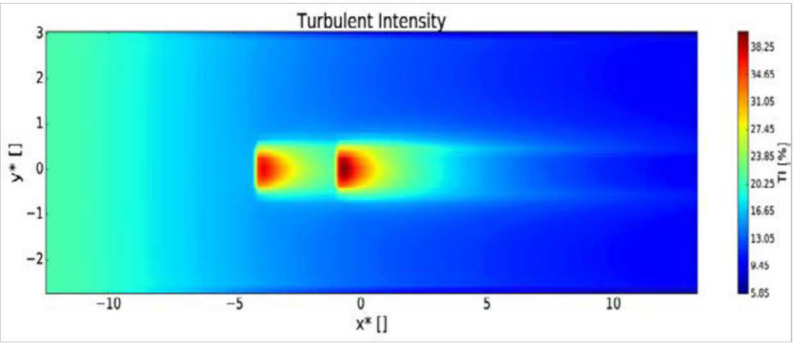

SNL-Delft3D-CEC: CEC Module

Sandia National Laboratories

Water Power Program

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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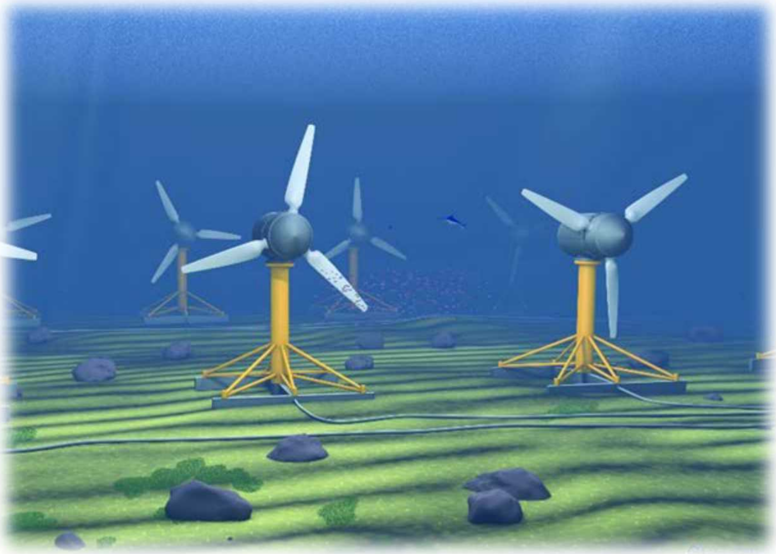
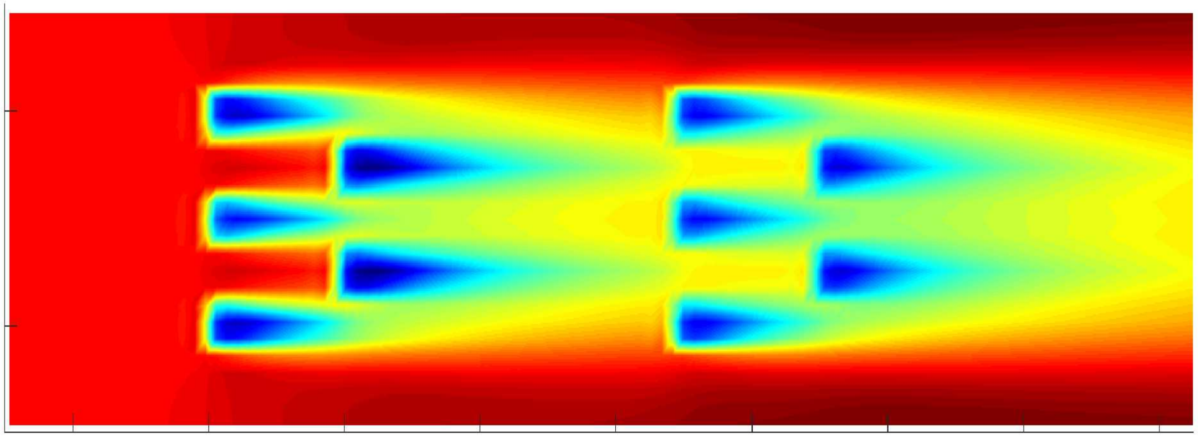
Current Energy Capture (CEC)

- Economic Concerns
  - Startup costs
  - Operation/maintenance costs
  - Power generation efficiency
  - Environmental impact
- Ecological Concerns
  - Water elevation/wake
  - Volumetric flow/tidal range
  - Sediment dynamics
  - Water quality



CEC Energy Extraction Representation

- CEC energy extraction manifests as:
  - Decreased momentum, *Q*
  - Altered turbulent kinetic energy (usually increased), *k*
  - Increased turbulence dissipation rate, ε
- These sources of momentum, turbulent kinetic energy, and turbulence dissipation are included in the conservation equations



Momentum Sink

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

$$\left(P_{\mathrm{CEC}} = \frac{1}{2} C_{\mathrm{T}} A_{\mathrm{CEC}} \rho U^3 \right)$$

K-ε Modifications

$$S_k = \frac{1}{2} C_{\mathrm{T}} A_{\mathrm{CEC}} \left(\beta_{\mathrm{p}} U^3 - \beta_{\mathrm{d}} U k \right)$$

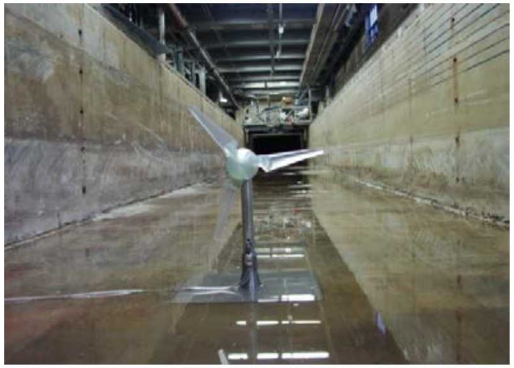
$$S_\varepsilon = C_{\varepsilon 4} \frac{\varepsilon}{k} S_k$$

Empirical constants

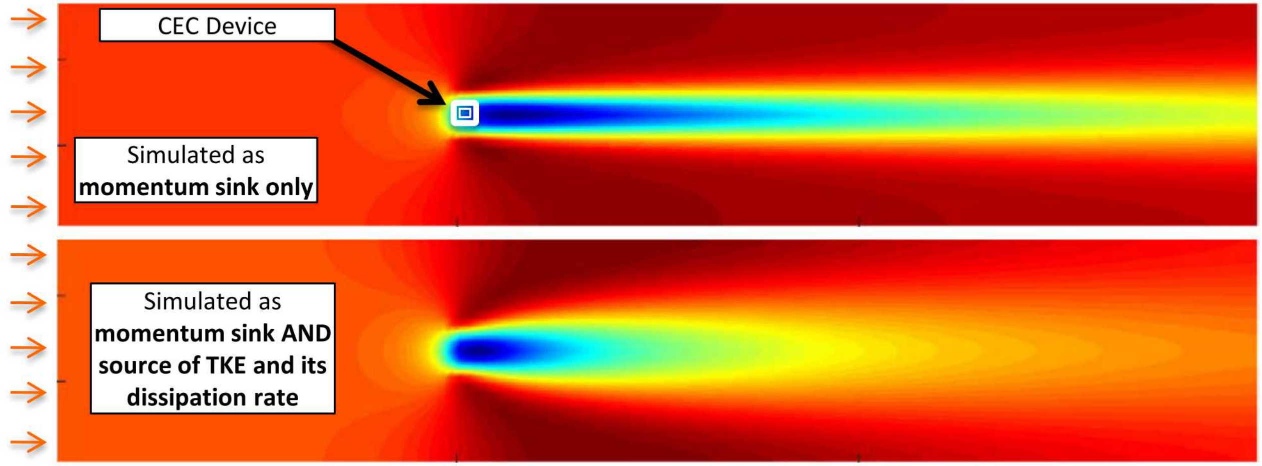
CEC Module Validation: Single Device

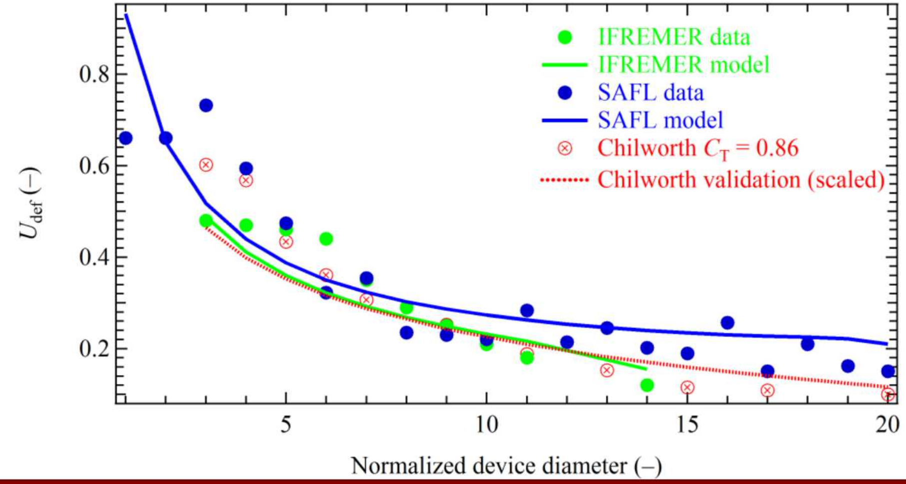
- SNL-Delft3D-CEC simulates the effects of CEC-devices on flow
- Laboratory data sets (turbines and actuator disks)

SAFL



IFREMER

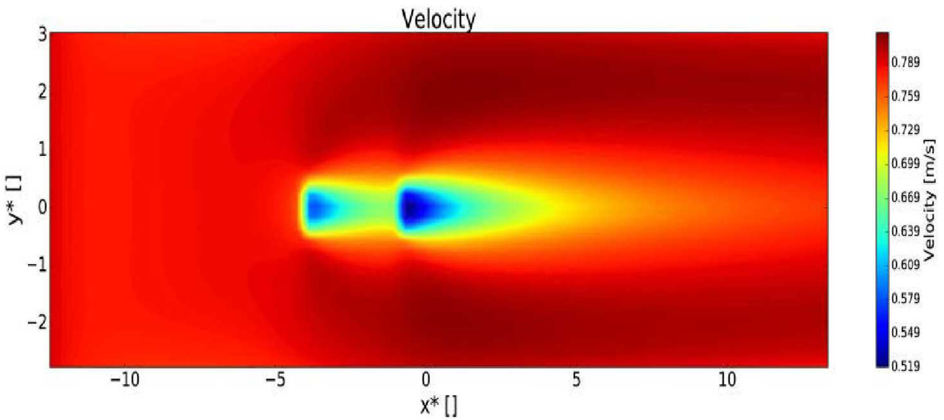


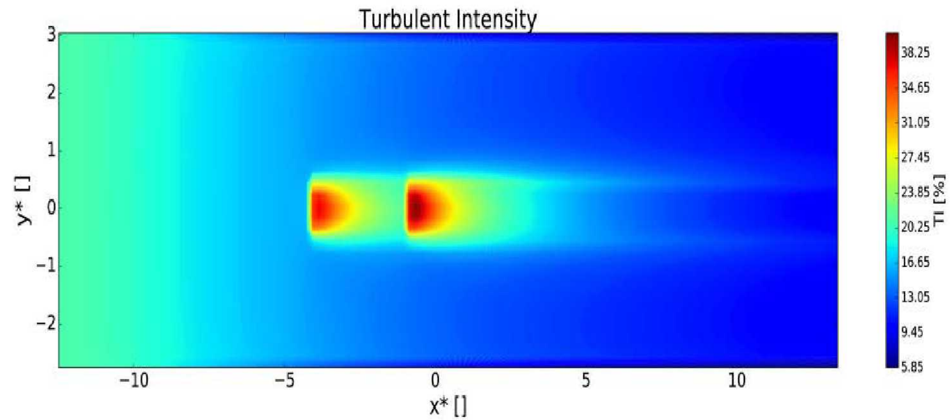


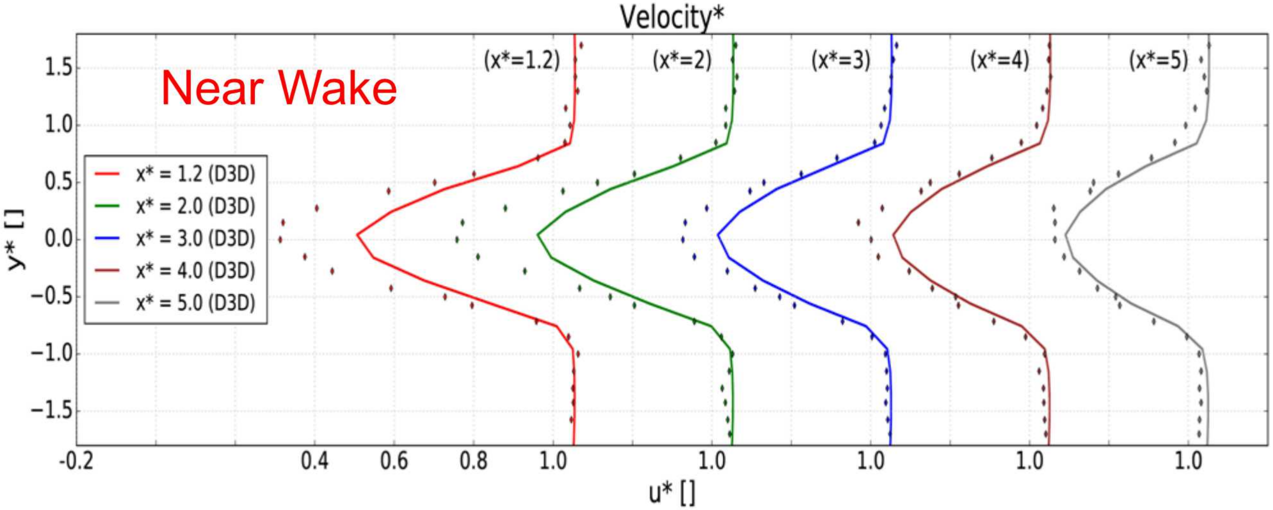
CEC Module Validation: Multiple Devices

Sandia National Laboratories

- CEC series data set (Mycek et al., 2014) using scaled turbines
- Shear and wake interactions are observed and simulated

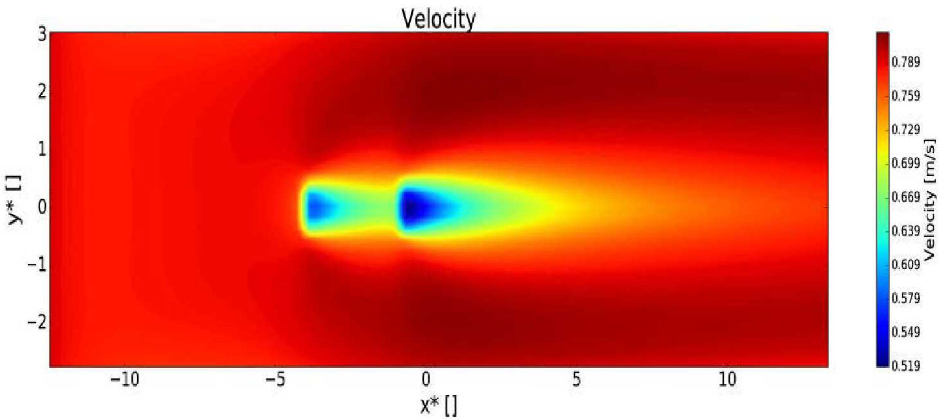


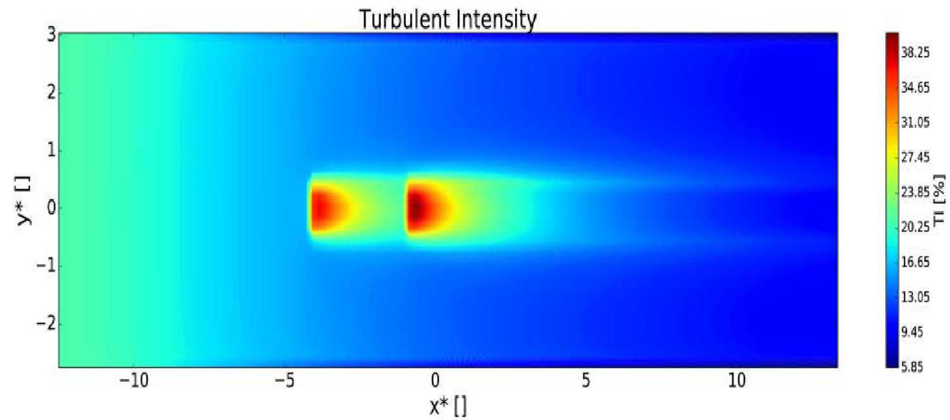


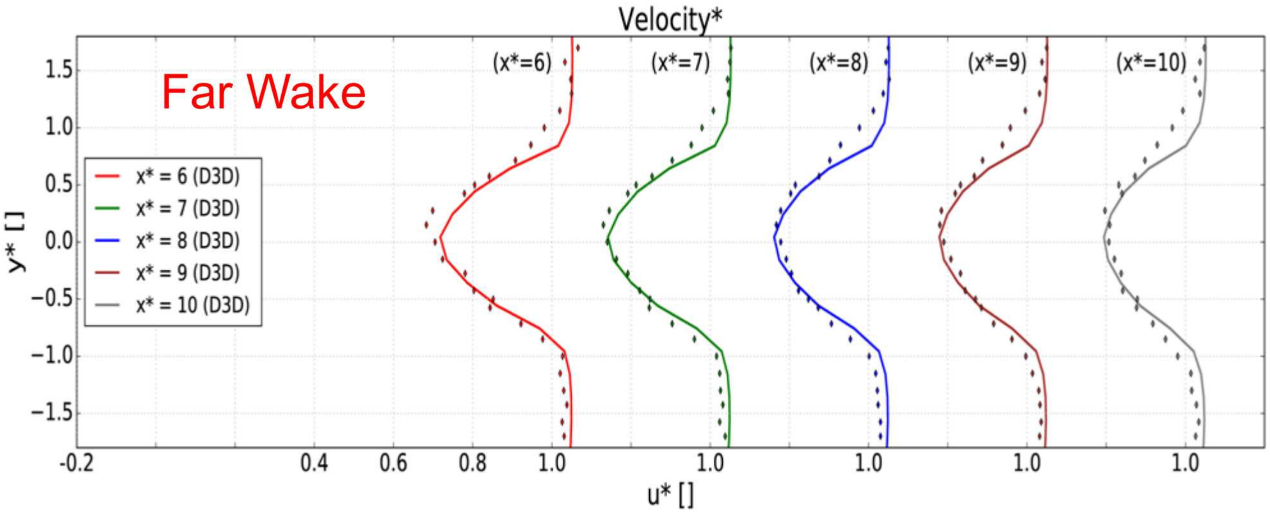


CEC Module Validation: Multiple Devices

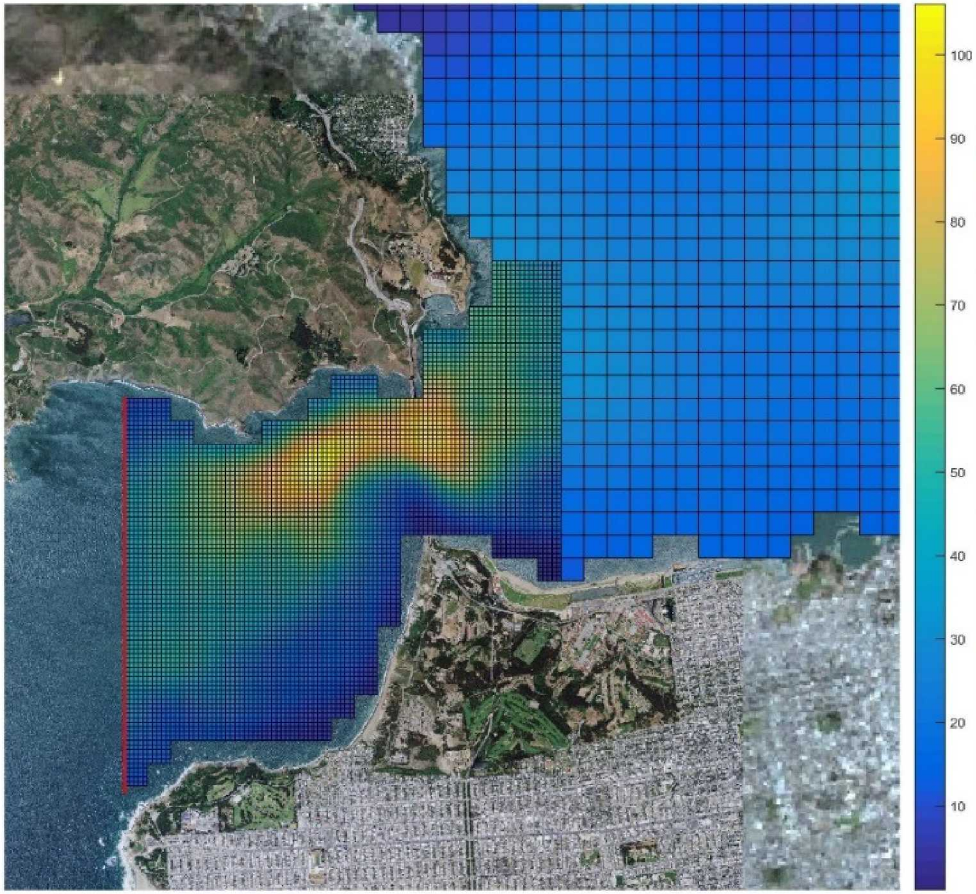
- CEC series data set (Mycek et al., 2014) using scaled turbines
- Shear and wake interactions are observed and simulated

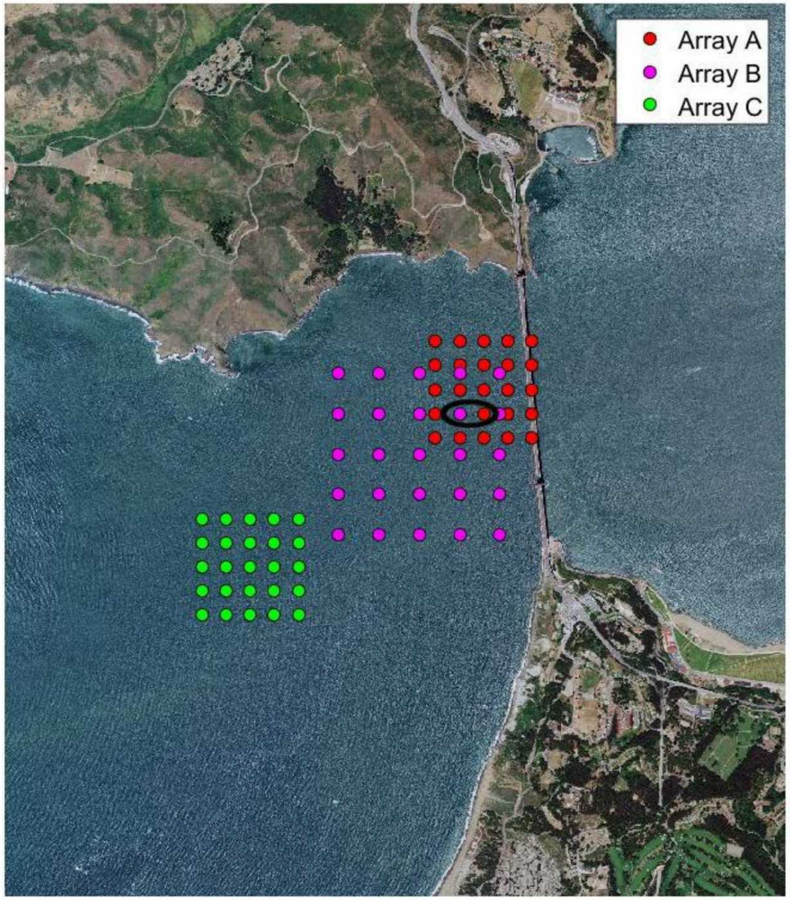




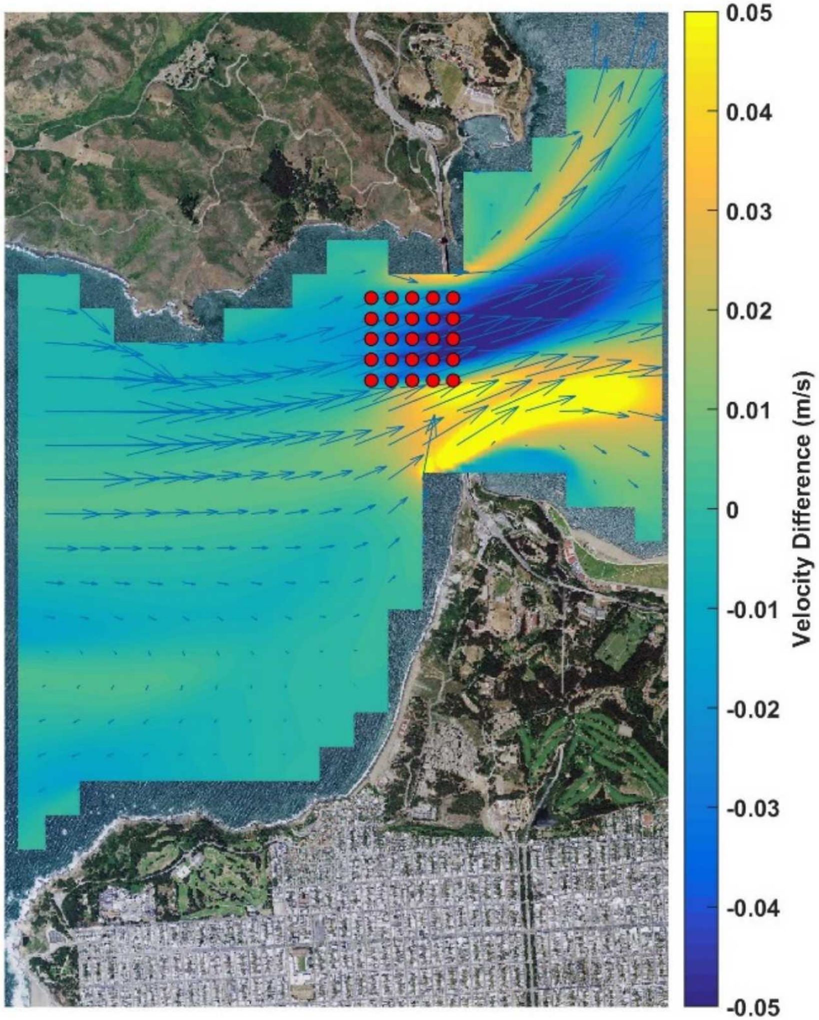


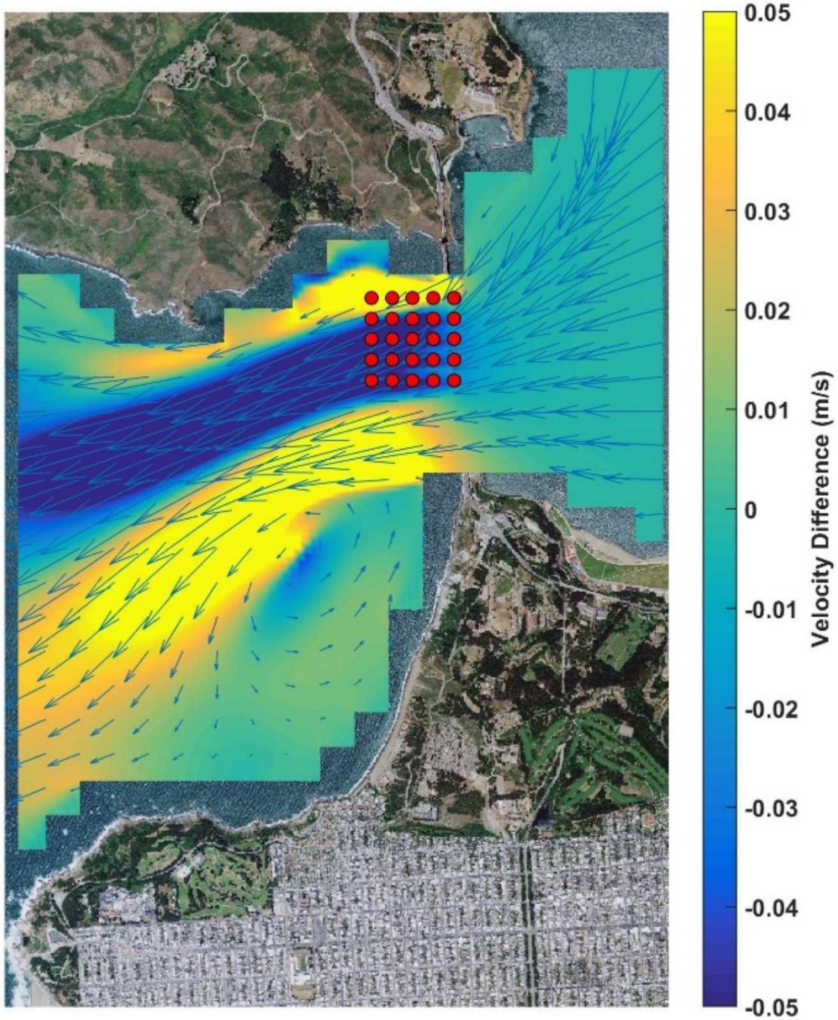
San Francisco Bay Model



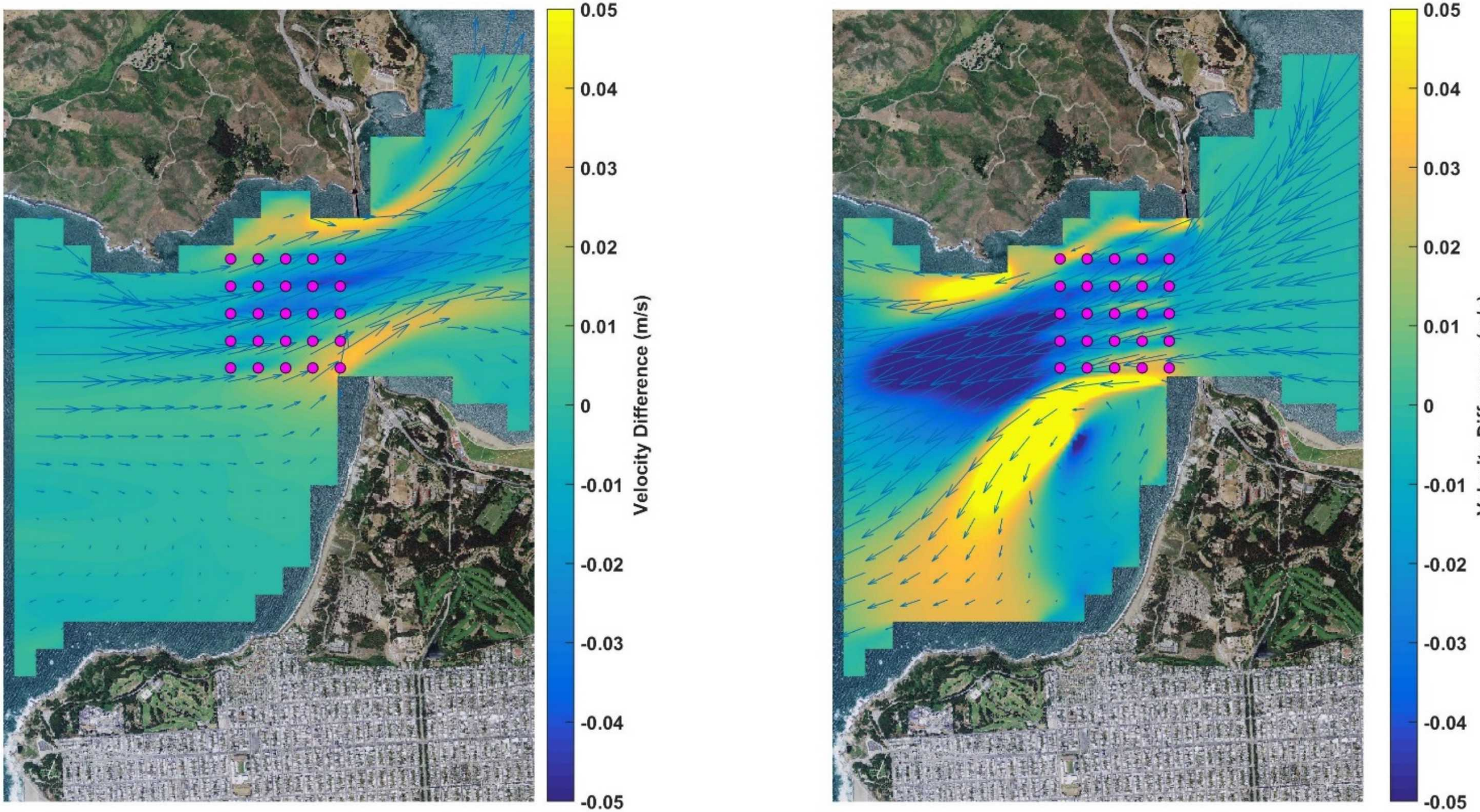


Flow Through Array A

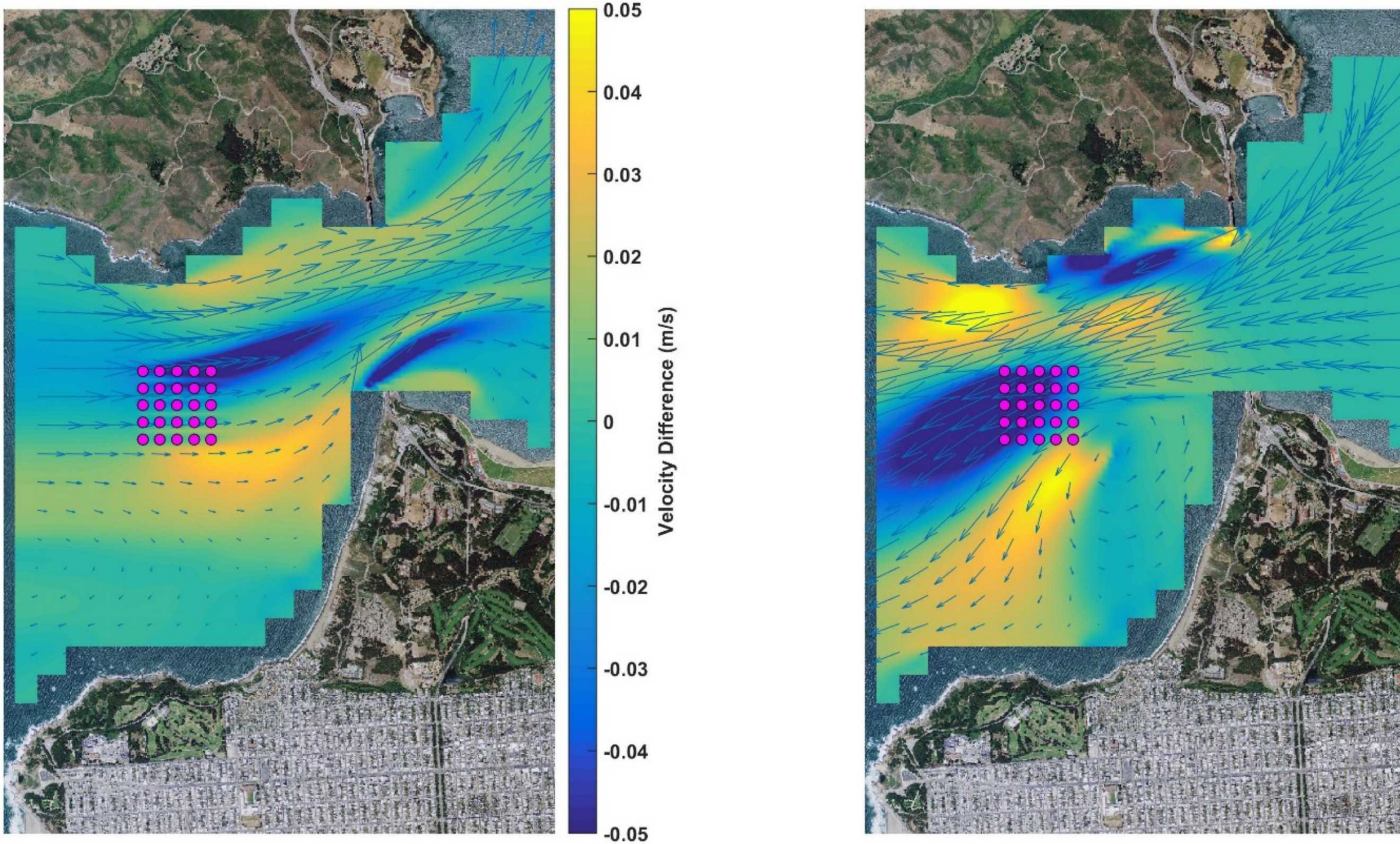




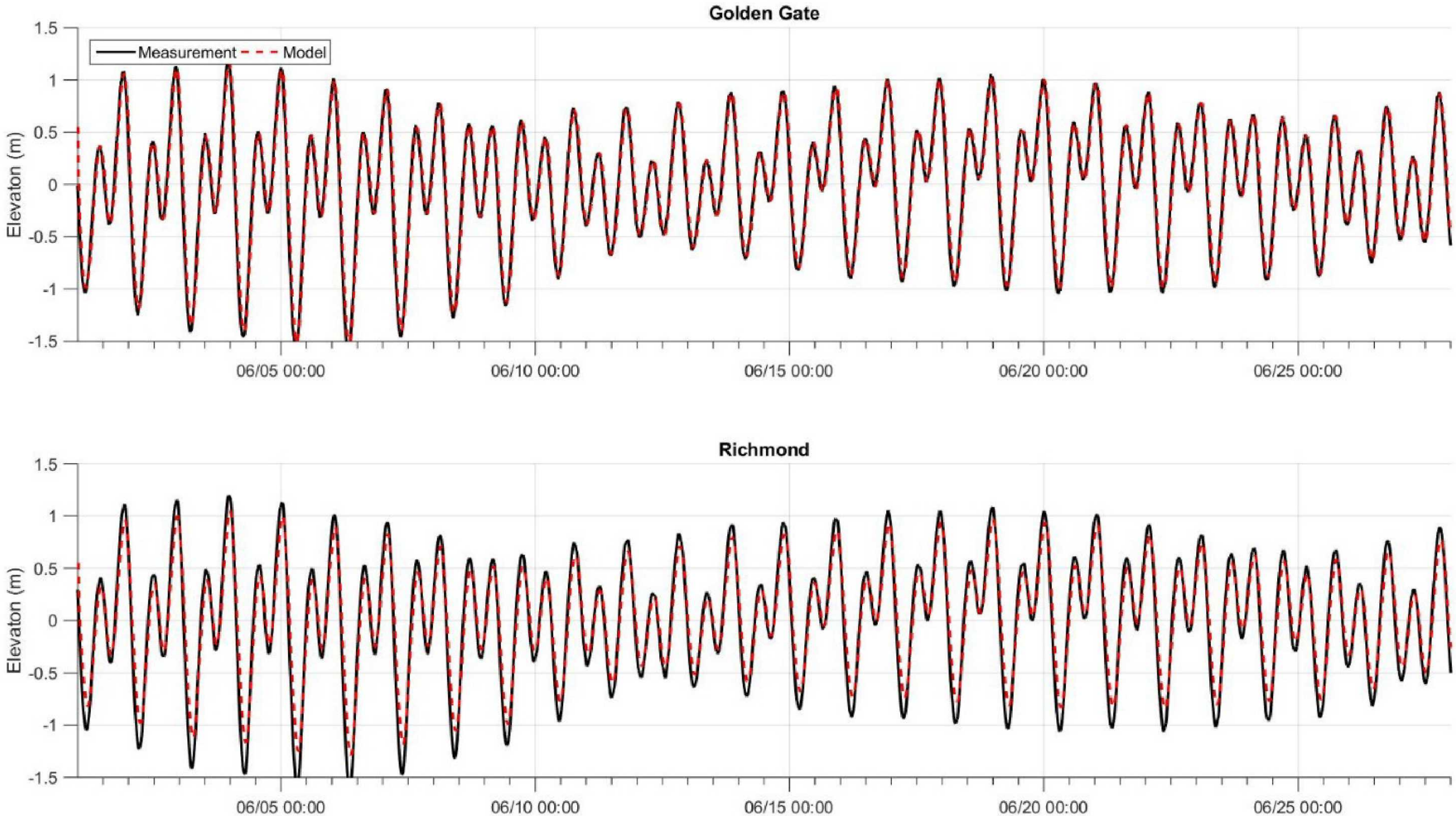
Flow Through Array B



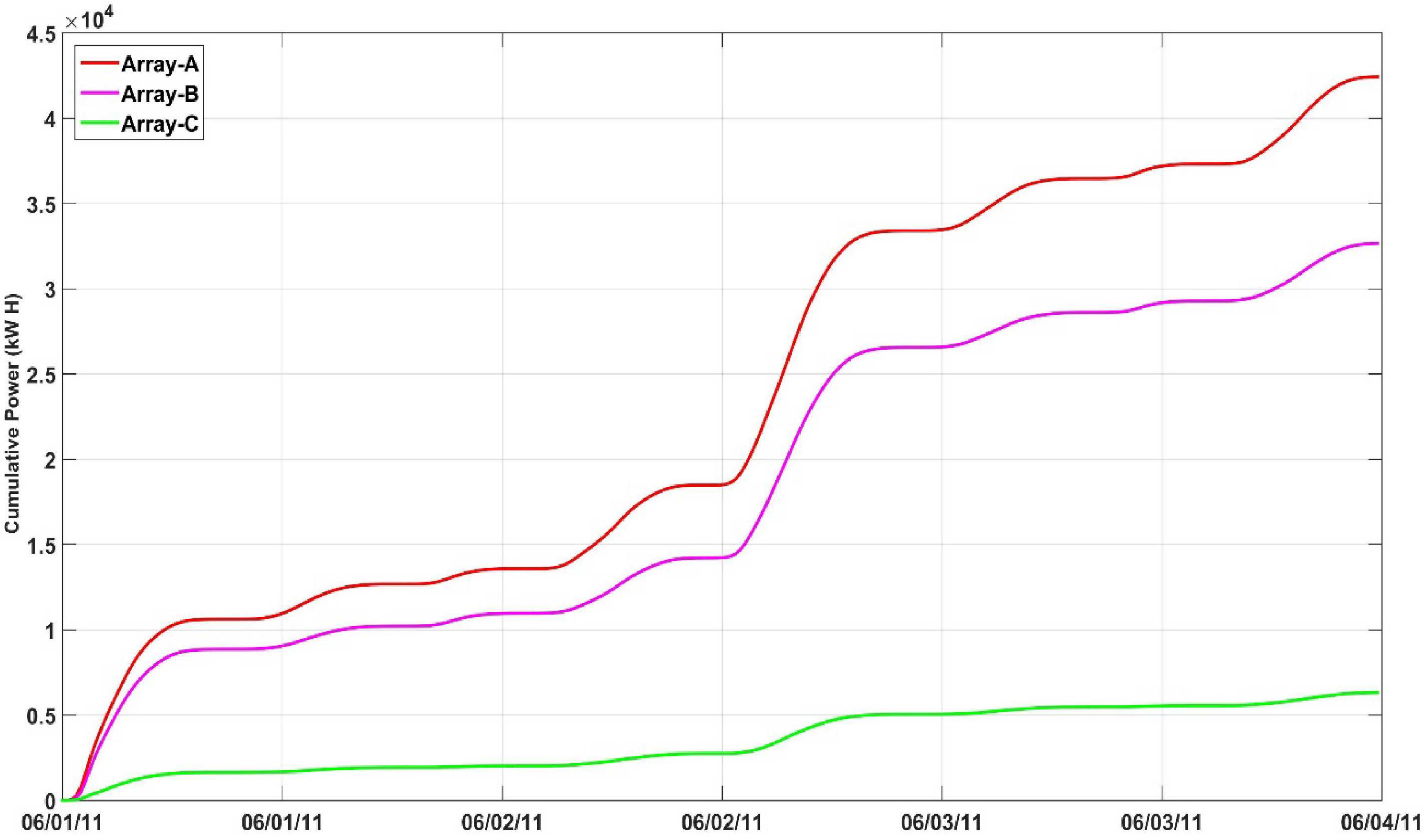
Flow Through Array C



San Francisco Bay Model

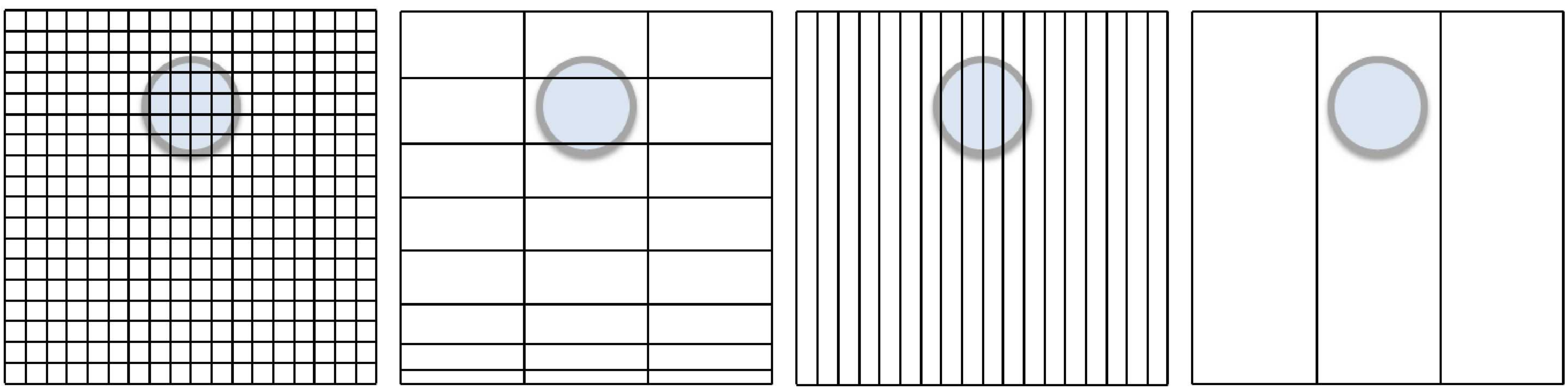


Power Generation



CEC Implementation

The CEC device acts as a momentum sink and source of k-ε in the 2D and 3D momentum and turbulence equations whether the device spans single or multiple grid cells in the vertical (z) or lateral (n) directions.

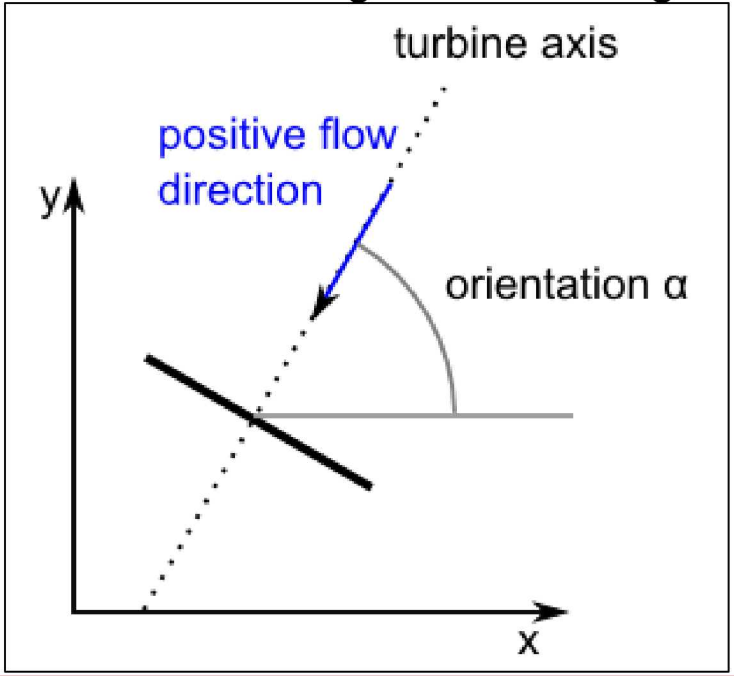


n/z-supergrid　n-sub/z-supergrid　z-sub/n-supergrid　n/z-subgrid

CEC Implementation

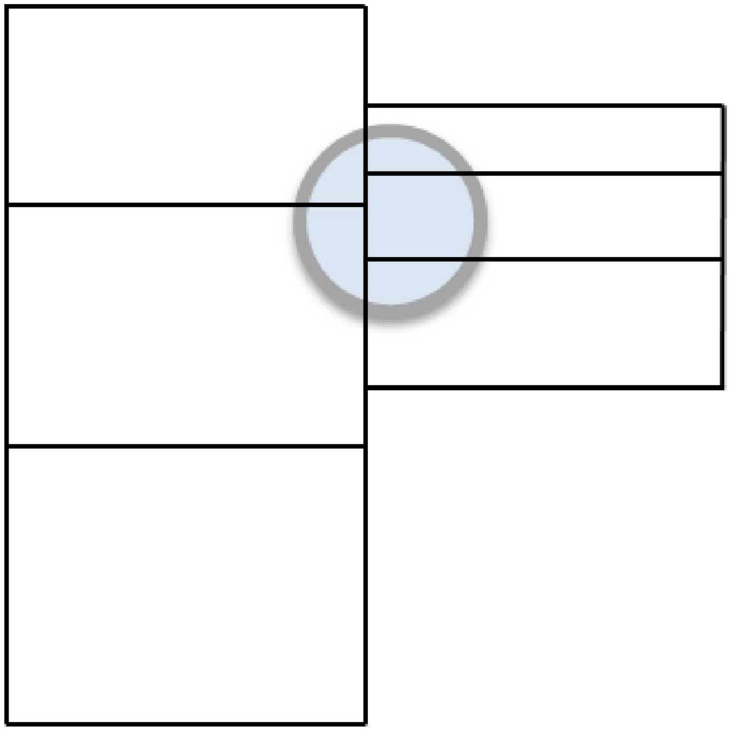
The CEC device is modeled as a flat actuator disc with negligible thickness in the streamwise direction. It is assumed that the grid is locally oriented such that cell boundaries align with the lateral direction (*n*) of the device. Position is assigned with (*x*,*y*) coordinates with orientation given by the angle α between the turbine axis and the positive *x*/latitude-coordinate axis ("east"). The orientation defines both the general orientation of the tidal turbine and the direction of positive flow through the turbine, i.e. α indicates which direction the turbine is facing with incoming flow defined as positive.

Note that the grid and flow-facing area of the CEC device are assumed to be aligned. A warning will be issued if not.



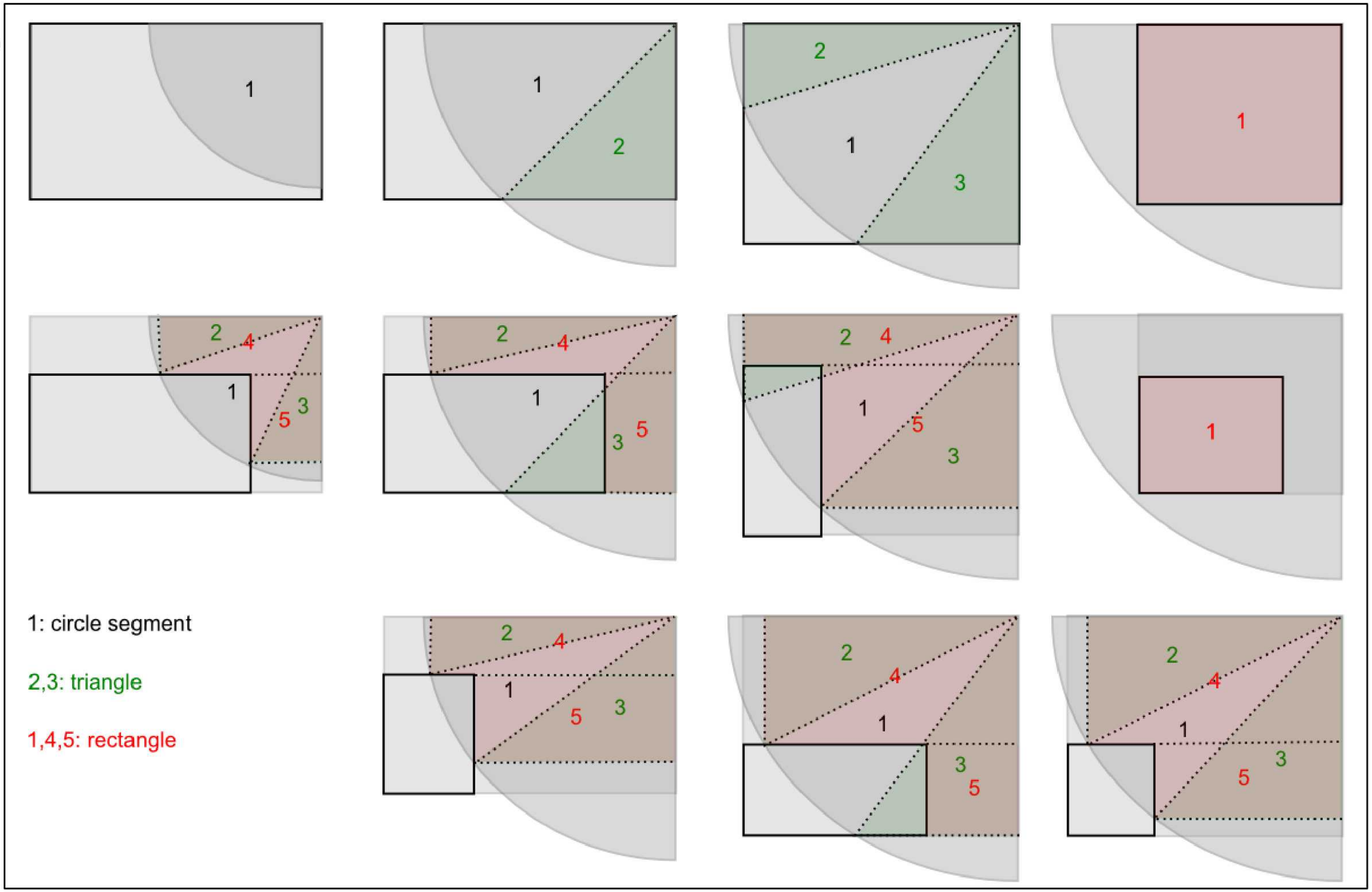
CEC Implementation

Implementation considers uneven bed levels and unequal water-surface levels in the lateral (*n*) direction. Although greatly exaggerated in the figure below, it is possible for the number of impacted layers to vary between grid cells. Slopes of σ planes are neglected.



CEC Implementation

The area of each cell occupied by the CEC device is explicitly calculated.

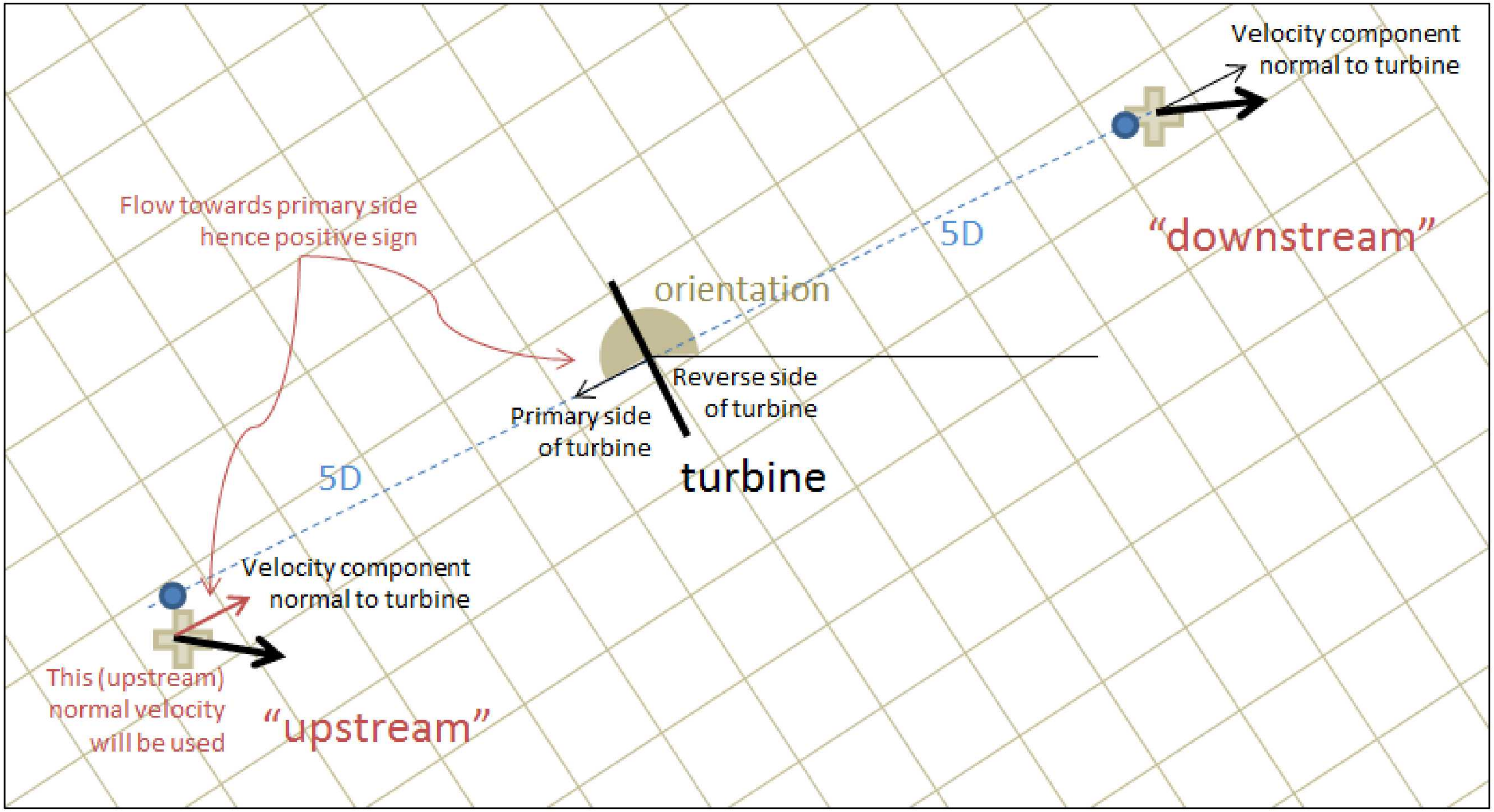


CEC Implementation

- A scalar velocity is needed to query the thrust curve although it must have a sign to indicate whether flow hits the turbine from the primary or reverse side. The local normal velocity cannot be used because it is influenced by the presence of the turbine. Instead, the velocity vector at the (vertical) level of the turbine axis in the centers of the corresponding grid cells at two locations ***X*** number of turbine diameters away from the turbine along the turbine axis (where ***X*** is given by the NDiaDist4Vel keyword) are determined. If both of these point in the same direction, the upstream value is used (otherwise the average is used) as the "reference velocity" to query the thrust and power tables.
- This algorithm has not yet been implemented for spherical coordinates. Also, it is assumed that the points of the "reference velocity" are located inside the grid and that the bed level does not change to such a degree that the turbine axis is below the bed or above the water level at either one of these points.

CEC Implementation

“Reference velocity” locations



CEC Implementation

Using the reference velocity, the analytical thrust is computed as:

$$F_{\mathrm{thrust}} = \frac{1}{2} C_{\mathrm{T}} A_{\mathrm{CEC}} \rho U_{\mathrm{ref}}^{2}$$

where A_{CEC} is the turbine area ($\frac{1}{4}\pi D^2$) and ρ is the water density (assumed 1000 kg/m^3).

The analytical power is computed as:

$$P = \frac{1}{2} C_{\mathrm{P}} A_{\mathrm{CEC}} \rho U_{\mathrm{ref}}^{3}$$

These quantities area available in the `trih` output file.

CEC Implementation

The actual energy loss in the simulation (the effective simulated thrust) depends on the loss coefficient C_L and the local velocity. To match the actual energy loss in the hydrodynamic simulation to the analytical thrust acting on the turbine, the loss coefficient is computed as

$$C_{\mathrm{L}} = \frac{\frac{1}{2} C_{\mathrm{T}} A_{\mathrm{CEC}} \rho U_{\mathrm{ref}}^2}{\sum_{n,k} A_{n,k} u_{0_{n,k}}^2}$$

The simulated thrust deviates from the analytical value because the energy loss term is included implicitly. Ultimately, the simulated thrust is computed as:

$$C_{\mathrm{T}}^{'} = C_{\mathrm{L}} \rho \sum_{n,k} A_{n,k} u_{0_{n,k}} u_{1_{n,k}}$$

Turbines.ini Inputs

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 2#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Explanation of the Turbines.ini Inputs. This example is the turbine for the East River Model.

Turbines.ini Inputs: CurvesFil

Parameter	Value
CurvesFil	**#curves.trb#**
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 2#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

File that describes turbine performance. Specifically, the velocity-dependent thrust and power coefficients.

Turbines.ini Inputs: Name

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Parameter	Value
CurvesFil	#curves.trb#
Name	**EastRiver**
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Name of the turbine.

Turbines.ini Inputs: Diameter

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	**2.0**
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Diameter of the turbine's swept blade area. Assumed circular shape.

Turbines.ini Inputs: XYLoc

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	**588980, 4513068**
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

(*x*,*y*) coordinates of the center of the circular turbine. These coordinates must correspond to the model coordinate system.

Turbines.ini Inputs: Orientation

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	**49.5**
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

The anticlockwise orientation of the turbine. 0° is down the positive x-axis ("East"). Turbines must align with the cell grid and face into the flow. This flow is Southwest.

Turbines.ini Inputs: VertPos

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	**#fixed#**
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Specifies whether the vertical position of the turbine is #fixed# or #variable#, which happens when the turbine is suspended from a barge.

Turbines.ini Inputs: AxisLevel

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Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	**-7.0**
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Vertical position of the center of the turbine with respect to the reference elevation if #fixed# or depth below the water surface if #variable#

Turbines.ini Inputs: ThrustCurve

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	**#Turbine Type 1#**
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Specifies which thrust curve to use from the #curves.trb# file.

Turbines.ini Inputs: PowerCurve

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	**#Turbine Type 1#**
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Specifies which power curve to use from the #curves.trb# file.

Turbines.ini Inputs: NDiaDist4Vel

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	**1.0**
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Number of turbine diameters upstream to use for the calculation of turbine power.

Turbines.ini Inputs: Beta_p

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	**0.95**
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	1

Turbulence parameter (canopy coefficient) that must be between 0 and 1.

Turbines.ini Inputs: Beta_d

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	**0.05**
Cep4	1.2
Cep5	1.2
TurbModel	1

Turbulence parameter (canopy coefficient).

Turbines.ini Inputs: Cep4 and Cep5

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	**1.2**
Cep5	**1.2**
TurbModel	1

Turbulence parameters (canopy coefficients). These are the turbulence closure constants.

Turbines.ini Inputs: TurbModel

Parameter	Value
CurvesFil	#curves.trb#
Name	EastRiver
Diameter	2.0
XYLoc	588980, 4513068
Orientation	180
VertPos	#fixed#
AxisLevel	-7.0
ThrustCurve	#Turbine Type 1#
PowerCurve	#Turbine Type 1#
NDiaDist4Vel	1.0
Beta_p	0.95
Beta_d	0.05
Cep4	1.2
Cep5	1.2
TurbModel	**1**

Specifies whether to use (1) or not (0) the model that alters turbulence due to the turbine.

Curves.trb Example

```
table-name 'Turbine Type 1     '
parameter  'velocity             ' unit '[m/s]'
parameter  'thrust coefficient' unit '[ - ]'
parameter  'power coefficient ' unit '[ - ]'
-99.0 .72000000  .9
-3.0  .72000000  .9
-2.0  .72000000  .7
-1.0  .72000000  .5
 0.0  .72000000  .1
 1.0  .72000000  .5
 2.0  .72000000  .7
 3.0  .72000000  .9
99.0  .72000000  .9
```

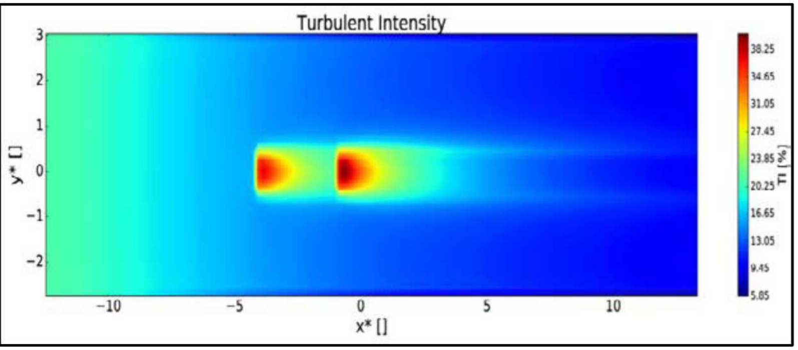
This file may contain multiple turbine types. This sequence of inputs must be repeated for each turbine with a unique name assigned to it on the first line.

Curves.trb Inputs

- This file allows specification of velocity-dependent thrust and power coefficients.
- The “table-name” must match the “CurvesFil” name specified in turbines.ini.
- The first column of numbers (parameter) is the velocity.
- The second column of numbers (parameter) is the corresponding thrust coefficient.
- The third column of numbers (parameter) is the power coefficient.

Conclusions

- This work demonstrates how modeling can be used to estimate environmental impacts from marine renewable energy projects (i.e., changes to circulation, sediment dynamics, and water quality).
- San Francisco Bay is an example of the modeling potential.
- Delft3d (and SNL-EFDC) are open-source so that regulators, industry developers, etc. will have free access to the tool for independent studies.
  - It will help facilitate the easy and common communication of study results.
- Future work will deploy this modeling software at a real-world site for further verification.



Live Model Building Demo: SNL-Delft3D-CEC

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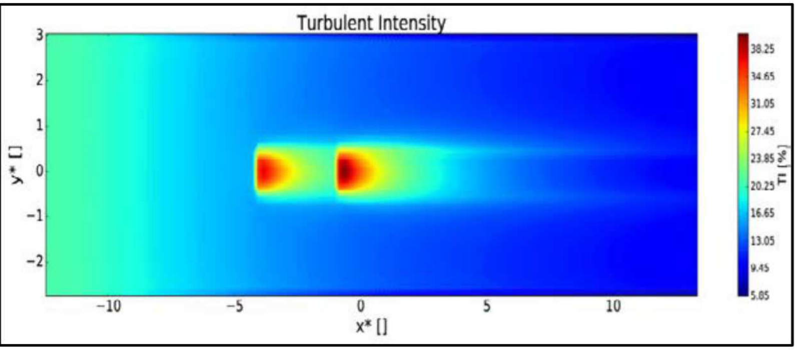

Best Practices: Conceptual Site Model Development

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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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 subsequent tiers will be updated as the site becomes better understood.

Model Development:
Typical Phased Approach

- **Tier 1**: Data compilation and initial Conceptual Site Model (CSM) development.
- **Tier 2**: Hydrodynamic modeling.
- **Tier 3**: Transport modeling (dye, temperature, sediment, water quality, CEC).

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 CEC.
- Evaluate CSM.

Hydrodynamic Model:

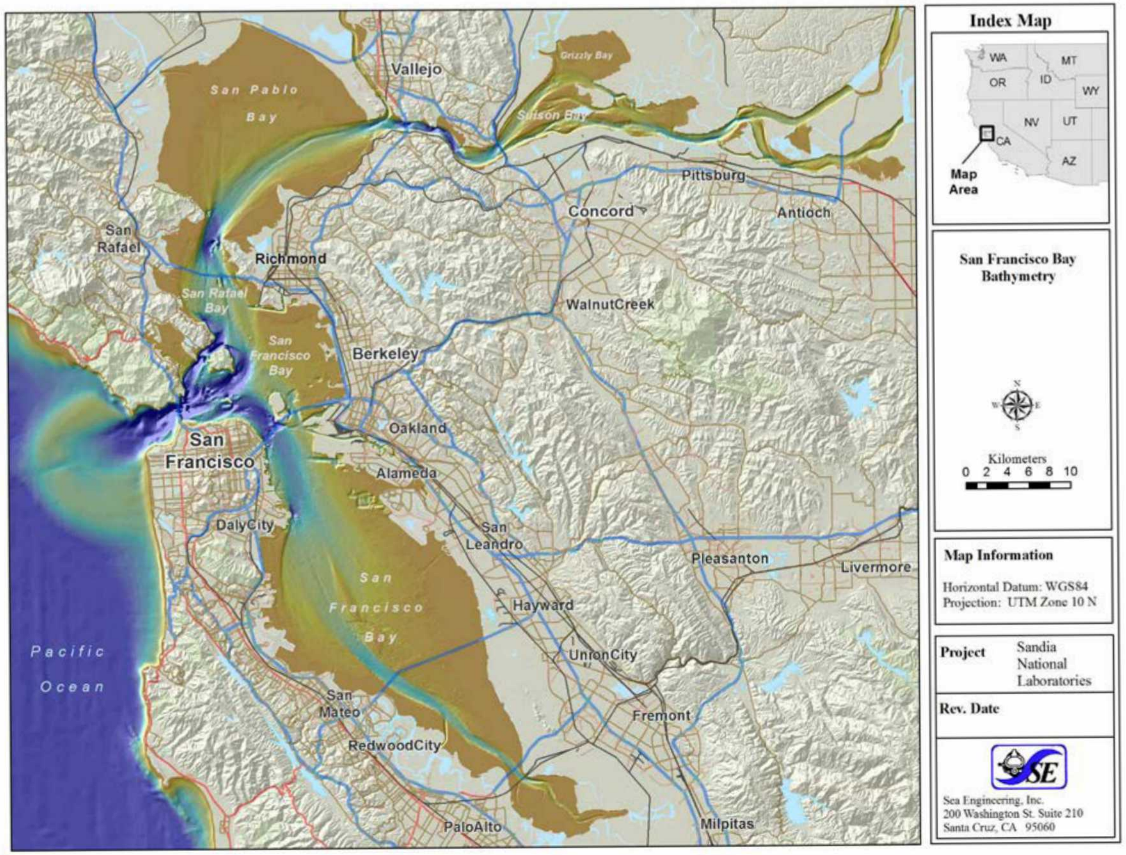
Typical Data Needs

- 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
- CEC characteristics
- For some studies, additional data needs may include:
  - Temperature
  - Salinity
  - Wind
  - Vegetation properties
  - Water-quality data

Hydrodynamic Model

Geometry and Bathymetry Data

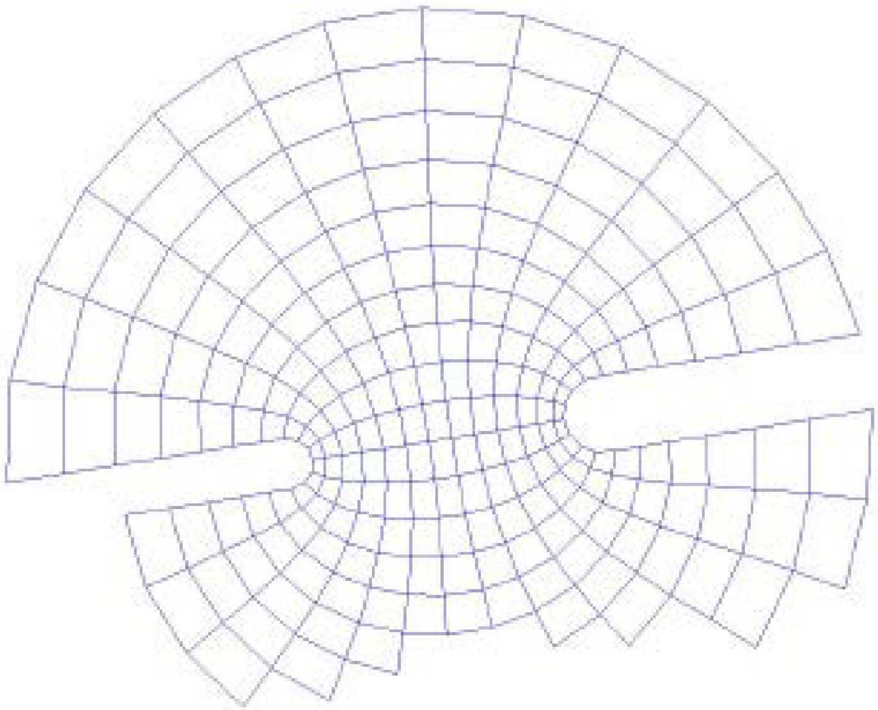
- Shoreline location
- Bathymetry
- Floodplain topography
- Data sources:
  - NOAA navigation charts
  - Bathymetry surveys
  - Laser altimetry surveys (LIDAR)



Hydrodynamic Model

Numerical Grid Generation (RGFGRID)

- Determine the extent of the model domain:
  - Establish 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.

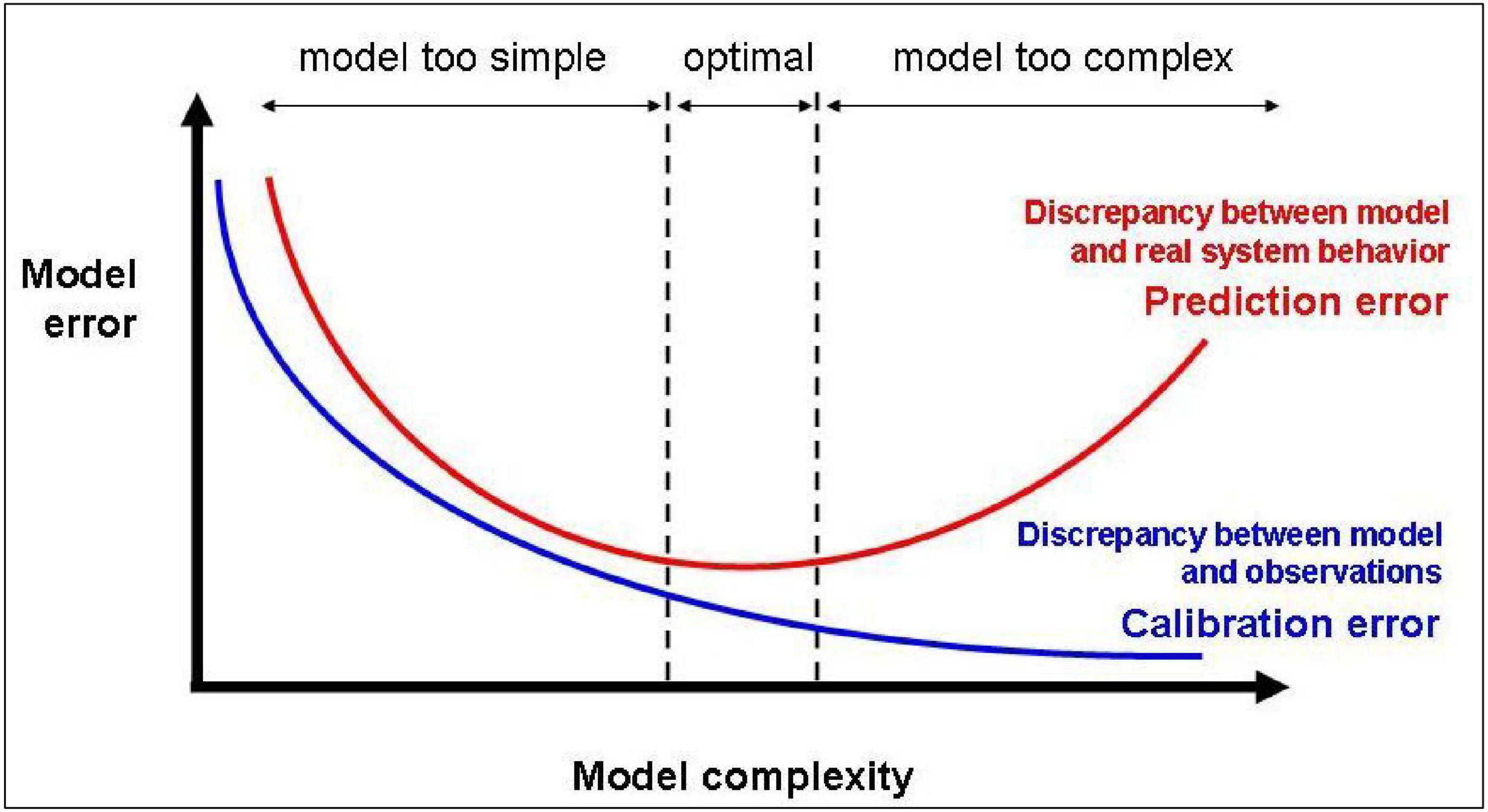
- Conduct short simulations over a wide range of flow and tidal conditions and verify results:
  - For floodplain and intertidal areas, ensure that wetting/drying of grid cells is working properly.
  - Animate results to examine entire study area.

Hydrodynamic Modeling Study

- Conduct a complete modeling study:
  - Calibration with appropriate data sets
  - Validation using "blind" simulations
  - Sensitivity testing
- Evaluate appropriateness of CEC parameters:
  - Are CEC 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.



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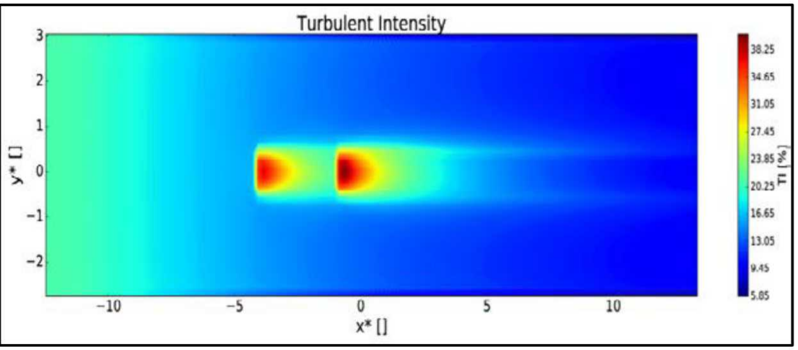


Appendix: Description of the Delft3D Turbulence Model

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Delft3D Horizontal/Vertical Mixing

- For 3D, the horizontal eddy viscosity coefficient, $\nu_H \gg \nu_V$, is the superposition of:
  1. Sub-grid scale (SGS) turbulence, ν_{SGS}.
  2. 3D turbulence, ν_V.
  3. Reynolds-averaged shallow-water equations, $\nu_H^{\mathrm{background}}$.

$$\nu_H = \nu_{\mathrm{SGS}} + \nu_V + \nu_H^{\mathrm{background}}$$

- Vertical mixing is the sum of:
  1. Water kinematic viscosity, ν_{mol}
  2. The greater of the computed mixing coefficient from the 3D turbulence-closure model or the spatiotemporal user-defined ambient or "background" mixing.

$$\nu_V = \nu_{\mathrm{mol}} + \max\left(\nu_{3\mathrm{D}}, \nu_V^{\mathrm{background}}\right)$$

Delft3D Turbulence Options

- Because turbulence processes are "sub-grid" scale, the primitive variables are space and time averaged and require *appropriate closure assumptions.*
- Four turbulence-closure models are available to determine the vertical eddy viscosity (ν_V) and vertical eddy diffusivity coefficient (D_V):
    1. Constant coefficient (user defined).
    2. Algebraic Eddy viscosity closure Model (AEM).
    3. *k-L* turbulence closure model.
    4. *k*-ε turbulence closure model (3D only).
- Each model calculates the turbulent kinetic energy (*k*), and its dissipation rate (ε) or mixing length (*L*) differently

#1 – User-Defined Constant Coefficient

- The user-specified eddy viscosity is related to the characteristic length and velocity scale (leads to a parabolic velocity profile as in laminar flow):

$$\nu_{3D} = \nu_V = c'_\mu L \sqrt{k}$$

- c'_μ is a calibration constant (user specified).
- L is the mixing length.
- k is the turbulent kinetic energy.

#1 – User-Defined Constant Coefficient

- This zero-order formulation calculates k and L algebraically:

$$L = \kappa(z+d)\sqrt{1-\frac{z+d}{H}}F_L(Ri)$$

- κ is the *von Kármán* constant ≈ 0.41.
- $F_L(Ri)$ is a damping function for stratified flow that depends upon the Richardson number, *Ri.*

#1 – User-Defined Constant Coefficient

- Stratification stability, which limits vertical turbulent exchanges, is a function of the interaction between gravitational forces (buoyancy flux) and turbulent shear production.
- This is characterized through the Richardson number:

$$Ri = -\frac{g\dfrac{\partial \rho}{\partial z}}{\rho\left[\left(\dfrac{\partial u}{\partial z}\right)^2 + \left(\dfrac{\partial v}{\partial z}\right)^2\right]}$$

#1 – User-Defined Constant Coefficient

- The *Ri*-dependent damping function comes from a fit to laboratory data:

$$F_L(Ri) = \begin{cases} e^{-2.3Ri} & Ri \geq 0 \\ (1-14Ri)^{0.25} & Ri < 0 \end{cases}$$

#1 – User-Defined Constant Coefficient

- Vertical eddy diffusivity is a scaled form of the vertical eddy viscosity:

$$D_{3D} = D_V = \frac{v_{3D}}{\sigma_c}$$

- Where σ_c is the Prandtl-Schmidt number:

$$\sigma_c = \sigma_{c_0} F_\sigma (Ri)$$

#1 – User-Defined Constant Coefficient

σ_c	Substance
0.7	*T*, *S*, scalars
1.0	Sediment
1.0	*k* in *k*-*L* and *k*-ε models
1.3	ε in *k*-ε model

#1 – User-Defined Constant Coefficient

- The damping function for vertical eddy diffusivity uses the Munk-Anderson formula:

$$F_L(Ri) = \begin{cases} \dfrac{(1+3.33Ri)^{1.5}}{\sqrt{1+10Ri}} & Ri \geq 0 \\ 1 & Ri < 0 \end{cases}$$

#1 – User-Defined Constant Coefficient

- Vertical eddy diffusivity:

$$D_V = \max\left(D_{3D}, 0.2 L_{oz}^2 \sqrt{-\frac{g}{\rho}\frac{\partial \rho}{\partial z}} \right)$$

- Where L_{oz} is the user-specified Ozmidov length scale.
- Use an ambient eddy diffusivity of 10^{-4} to 10^{-5} depending on the Prandtl-Schmidt number.

#2 – Algebraic Eddy Model (AEM)

- The algebraic closure (ALG) model assumes a logarithmic velocity profile leading to a linear relation between *k* at the bed and *k* at the free surface:

$$k = \frac{1}{\sqrt{c_\mu}}\left[\left(u_*^b\right)^2\left(1-\frac{z+d}{H}\right)+u_{*_s}^2\frac{z+d}{H}\right]$$

- Where $c_\mu \approx 0.09$ calibrated for local-equilibrium shear layers.
- u_{*_s} is the friction velocity at the free surface.
- u_*^b is the modified bed friction velocity, u_{*_b}.

#2 – Algebraic Eddy Model (AEM)

- The magnitude of the bed friction velocity is determined from the flow speed in the first grid point above the bed assuming a logarithmic velocity profile:

$$\vec{u}_{*b} = \frac{\kappa}{\ln\left(1 + \frac{\Delta z_b}{2 z_0}\right)} \vec{u}_b$$

- The friction velocity at the free surface is dependent upon the wind velocity 10 m above the free surface.

#2 – Algebraic Eddy Model (AEM)

- The Prandtl Mixing Length (PML) model assumes instantaneous local equilibrium between production and dissipation in the *k*-*L* model:

$$k = \frac{1}{\sqrt{c_\mu}} L^2 \left[\left(\frac{\partial u}{\partial z} \right)^2 + \left(\frac{\partial v}{\partial z} \right)^2 \right]$$

- With mixing length, *L*, as given in Turbulence Option #1 (user defined).

#3 – *k*-*L* Turbulence-Closure Model

- In the *k*-*L* model, the mixing length is prescribed as in Turbulence Option #1.
- The turbulent kinetic energy term, k, is calculated from a transport equation that includes:
  - An energy dissipation term
  - A buoyancy term
  - A production term
- Two additional assumptions:
  - Production, buoyancy, and dissipation are dominant.
  - Horizontal length scales are much larger than vertical (shallow water, boundary layer flow).

#3 – *k*-*L* Turbulence-Closure Model

- The non-conservative form of the transport equation is solved:

$$\frac{\partial k}{\partial t} + u\frac{\partial k}{\partial x} + v\frac{\partial k}{\partial y} + \frac{w}{H}\frac{\partial k}{\partial \sigma} =$$

$$\frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(D_k\frac{\partial k}{\partial \sigma}\right) + P_k + P_{kw} + B_k - \varepsilon$$

#3 – *k*-*L* Turbulence-Closure Model

- In the preceding equation:

$$D_k = \frac{\nu_{\mathrm{mol}}}{\sigma_{\mathrm{mol}}} + \frac{\nu_{3D}}{\sigma_c}$$

- Where ν_{mol} is the kinematic molecular viscosity.
- σ_{mol} is the Prandtl-Schmidt number for molecular mixing (700 for *S* and 6.7 for *T*).
- σ_c is the Prandtl-Schmidt number (defined in previous table, slide 39).

#3 – *k*-*L* Turbulence-Closure Model

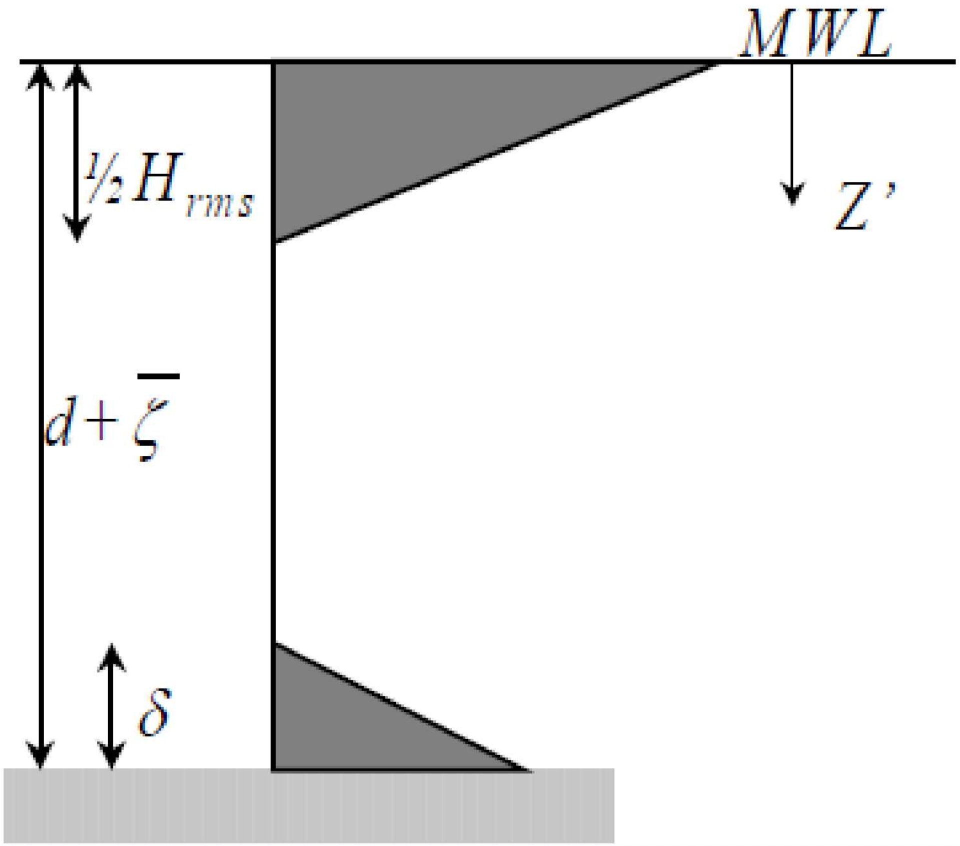
- For production of *k*, horizontal gradients of horizontal velocity and all gradients of vertical velocity are neglected:

$$P_k = \nu_{3D} \frac{1}{H^2}\left[\left(\frac{\partial u}{\partial \sigma}\right)^2 + \left(\frac{\partial v}{\partial \sigma}\right)^2\right]$$

- A “partial slip” option is available for small-scale applications (e.g., simulations of laboratory flumes).

#3 – *k*-*L* Turbulence-Closure Model

- Vertical distribution of turbulent kinetic energy production and dissipation due to waves, $P_{kw}(z')$ and $P_{\varepsilon w}(z')$, respectively.



#3 – *k*-*L* Turbulence-Closure Model

- Near the surface, the contribution due to breaking waves is distributed over the half wave height below the mean water surface, $H_{\text{rms}}/2$:

$$P_{kw}(z') = \frac{4D_w}{\rho H_{\text{rms}}}\left[1 - \frac{2z'}{H_{\text{rms}}}\right] \quad \text{for } 0 \le z' \le \frac{1}{2}H_{\text{rms}}$$

- Where *z’* is the vertical coordinate originating from the wave-averaged water level and positive downward and δ is the wave boundary-layer thickness described later.
- D_w (W/m^2) is the areal energy density of the waves (from SWAN).
- And ρ is the water density.

#3 – *k*-*L* Turbulence-Closure Model

- Near the bottom, the contribution due to bottom friction is linearly distributed over the wave boundary layer:

$$P_{kw}(z') = \frac{2D_f}{\delta}\left(1 - \frac{H - z'}{\delta}\right) \text{ for } H - \delta \le z' \le H$$

- Where δ is the thickness of the wave boundary layer.

#3 – *k*-*L* Turbulence-Closure Model

- The thickness of the wave boundary layer is:

$$\delta = H \min\left[0.5, \max\left[\frac{e\overline{z}_0}{H}, 0.09\frac{k_s}{H}\left(\frac{u_{\mathrm{orb}}}{\omega k_s}\right)^{0.82}\right]\right]$$

- Where the increased bed roughness due to waves is:

$$\overline{z}_0 = \frac{\Delta z_b}{\exp\left(\kappa\left|\frac{u_b}{\tilde{u}_*}\right|\right) - 1}$$

#3 – *k*-*L* Turbulence-Closure Model

- The ratio of bed shear-stress velocity to the shear-stress velocity due to waves and currents is:

$$\frac{u_b}{\tilde{u}_*} = \frac{1}{\kappa} \ln\left(1 + \frac{\Delta z_b}{2\bar{z}_0}\right)$$

- Where Δz_b is the thickness of the bottom model layer and $\bar{z}_0$ is the increased bed roughness due to waves.

#3 – *k*-*L* Turbulence-Closure Model

- On slide 51, the wave energy dissipation due to bottom friction is:

$$D_f = \frac{1}{2\sqrt{\pi}} \rho_0 f_w u_{\mathrm{orb}}^3$$

- Where the orbital velocity near the bed is:

$$u_{\mathrm{orb}} = \frac{\sqrt{\pi}}{4} \frac{H_{\mathrm{rms}}\omega}{\sinh(kH)}$$

- And the wave friction factor under oscillatory flow is:

$$f_w = \begin{cases} 0.00251 \exp\left[5.21 \left(\dfrac{u_{\mathrm{orb}}}{\omega k_s} \right)^{-0.19} \right] & \dfrac{u_{\mathrm{orb}}}{\omega k_s} > \dfrac{\pi}{2} \\ 0.3 & \dfrac{u_{\mathrm{orb}}}{\omega k_s} \leq \dfrac{\pi}{2} \end{cases}$$

#3 – *k*-*L* Turbulence-Closure Model

- On the preceding slide:
  - ω is the wave angular frequency, and
  - k_s is the Nikuradse roughness length scale, which can be used to estimate $z_0 = k_s/30$.

#3 – *k*-*L* Turbulence-Closure Model

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- The Dirichlet boundary condition at the bed is:

$$k\big|_{\sigma=-1} \frac{u_{*_b}^2}{\sqrt{c_\mu}}$$

- And at the surface is:

$$k\big|_{\sigma=0} = \underbrace{\frac{u_{*_s}^2}{\sqrt{c_\mu}}}_{\text{wind}} + \underbrace{\left(\frac{2D_w\kappa}{\rho c_D}\right)^{2/3}}_{\text{waves}}$$

- Where $c_D = c_\mu^{3/4} \approx 0.1925$ is a calibration constant.

#3 – *k*-*L* Turbulence-Closure Model

- At open boundaries assuming a logarithmic velocity profile and shear stresses at the bed and surface, the boundary condition is:

Bottom Wind Waves

$$k(z) = \frac{1}{\sqrt{c_\mu}}\left[u_{*_b}^2 \left(1 + \frac{z+d}{H}\right) + \frac{z+d}{H}\left[u_{*_s}^2 + \sqrt{c_\mu}\left(\frac{2 D_w \kappa}{\rho c_D}\right)^{2/3} \right]\right]$$

#3 – *k*-*L* Turbulence-Closure Model

- In stratified flows, turbulent kinetic energy is converted into potential energy through the buoyancy flux:

$$B_k = \frac{\nu_{3D}}{\rho \sigma_\rho} \frac{g}{H} \frac{\partial \rho}{\partial \sigma}$$

- Where ρ is the water density.
- And the Prandtl-Schmidt numbers are ρ_σ = 0.7 for salinity and temperature and ρ_σ = 1.0 for suspended sediments.

#3 – *k*-*L* Turbulence-Closure Model

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- Turbulent kinetic energy dissipation rate depends on the mixing length and turbulent kinetic energy:

$$\varepsilon = c_D \frac{k^{3/2}}{L}$$

- Where c_D is a calibration constant derived from c_μ in the k-ε model:

$$c_D = c_\mu^{3/4} \approx 0.1925$$

#4 – k-ε Turbulence-Closure Model

- Transport equations are solved for both the turbulent kinetic energy, k, and for the energy dissipation, ε.
- The mixing length is calculated from k and ε as:

$$L = c_D \frac{k^{3/2}}{\varepsilon}$$

- Assumptions include:
  - Production, buoyancy, and dissipation terms dominate (non-conservative transport allowed).
  - Horizontal length scales are larger than vertical.

#4 – *k*-*ε* Turbulence-Closure Model

- Transport equations:

$$\frac{\partial k}{\partial t}+u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}+\frac{w}{H}\frac{\partial k}{\partial \sigma}=\frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(D_k\frac{\partial k}{\partial \sigma}\right)+P_k+P_{kw}+B_k-\varepsilon$$

$$\frac{\partial \varepsilon}{\partial t}+u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}+\frac{w}{H}\frac{\partial \varepsilon}{\partial \sigma}=\frac{1}{H^2}\frac{\partial}{\partial \sigma}\left(D_\varepsilon\frac{\partial \varepsilon}{\partial \sigma}\right)+P_\varepsilon+P_{\varepsilon w}+B_\varepsilon-c_{2\varepsilon}\frac{\varepsilon^2}{k}$$

- With:

$$D_k=\frac{\nu_{\mathrm{mol}}}{\sigma_{\mathrm{mol}}}+\frac{\nu_{\mathrm{3D}}}{\sigma_c}$$

$$D_\varepsilon=\frac{\nu_{\mathrm{3D}}}{\sigma_\varepsilon}$$

#4 – *k*-ε Turbulence-Closure Model

- Turbulent kinetic energy production, P_k, is calculated the same as Turbulence Option #3 on slide 48.
- Turbulent kinetic energy production due to waves, P_{kw}, is calculated the same as Turbulence Option #3 on slide 49.

#4 – k-ε Turbulence-Closure Model

- P_{kw} along the bottom due to waves is the same as Turbulence Option #3 on slides 50-54.
- The Dirichlet boundary condition at the bed for k is the same as Turbulence Option #3 on slide 55.
- The open boundary condition at the bed for k is the same as Turbulence Option #3 on slide 56.

#4 – *k*-ε Turbulence-Closure Model

- The source term for P_ε is coupled to P_k as:

$$P_\varepsilon = c_{1\varepsilon} \frac{\varepsilon}{k} P_k$$

- Where $c_{1\varepsilon} = 1.44$.

#4 – *k*-ε Turbulence-Closure Model

- The source term for $P_{\varepsilon w}$ is coupled to P_{kw} as:

$$P_{\varepsilon w}(z') = c_{1\varepsilon} \frac{\varepsilon}{k} P_{kw}(z')$$

- Where $c_{1\varepsilon} = 1.44$.

#4 – *k*-ε Turbulence-Closure Model

- Turbulent kinetic energy dissipation through buoyancy flux is:

$$B_{\varepsilon} = c_{1\varepsilon} \frac{\varepsilon}{k} \left(1 - c_{3\varepsilon}\right) B_k$$

- Where:
  - $c_{1\varepsilon} = 1.44$
  - $c_{2\varepsilon} = 1.92$
  - $c_{3\varepsilon} = \begin{cases} 0 & \text{unstable stratification} \\ 1 & \text{stable stratification} \end{cases}$

#4 – *k*-ε Turbulence-Closure Model

- The Dirichlet boundary condition at the bed for turbulent energy dissipation rate is:

$$\varepsilon\big|_{\sigma=-1} \frac{u_{*b}^{3}}{\kappa \tilde{z}_{0}}$$

- And at the surface is:

$$\varepsilon\big|_{\sigma=0} = \underbrace{\frac{2u_{*s}^{3}}{\kappa \Delta z_{s}}}_{\text{wind}} + \underbrace{\frac{4D_{w}}{\rho H_{\text{rms}}}}_{\text{waves}}$$

#4 – *k*-ε Turbulence-Closure Model

- At open boundaries assuming a logarithmic velocity profile and shear stresses at the bed and surface, the boundary condition is:

$$\varepsilon(z) = \underbrace{\frac{u_{*b}^3}{\kappa(z+d)}}_{\text{bottom}} + \underbrace{\frac{u_{*s}^3}{\kappa(H-z-d)}}_{\text{wind}}$$

#4 – k-ε Turbulence-Closure Model

- Vertical eddy viscosity is:

$$\nu_{3D} = c'_{\mu} L \sqrt{k} = c'_{\mu} c_D \frac{k^2}{\varepsilon}$$