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Propeller Wash Model to Predict Ship Traffic-induced Resuspension and Redistribution of Sediments

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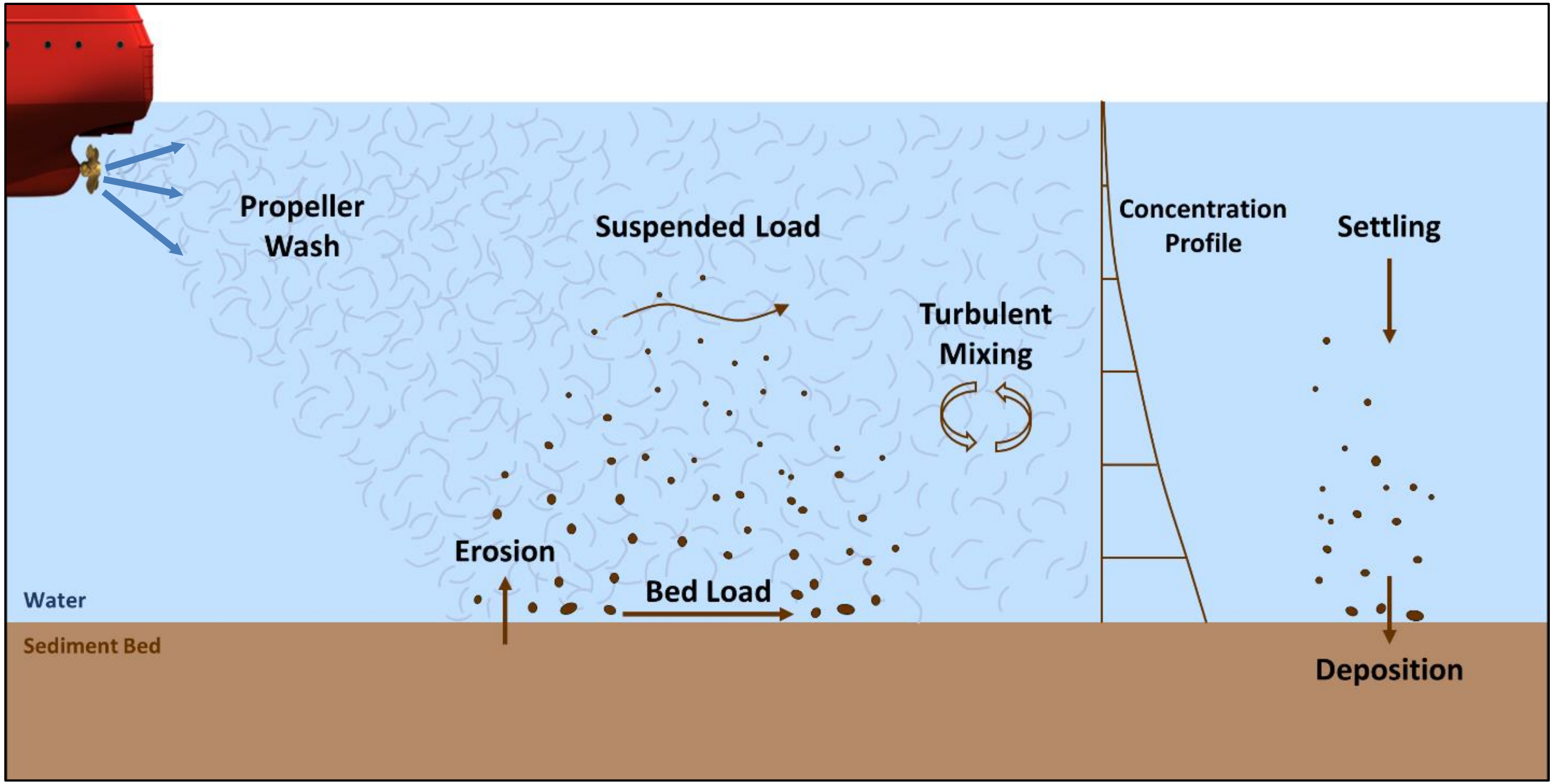
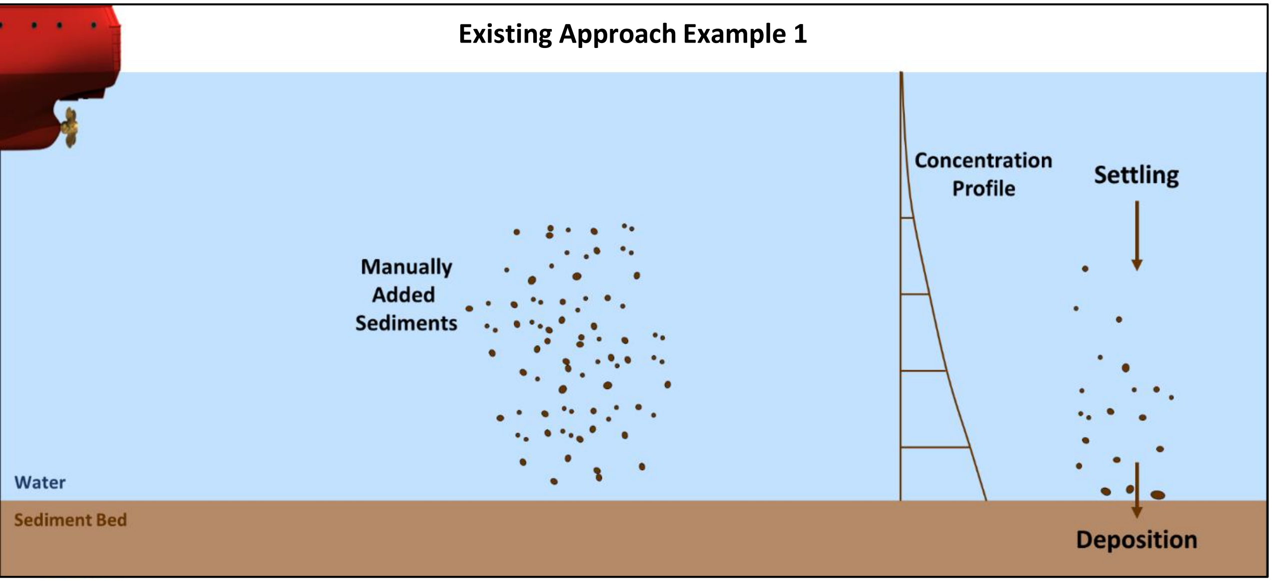
Background

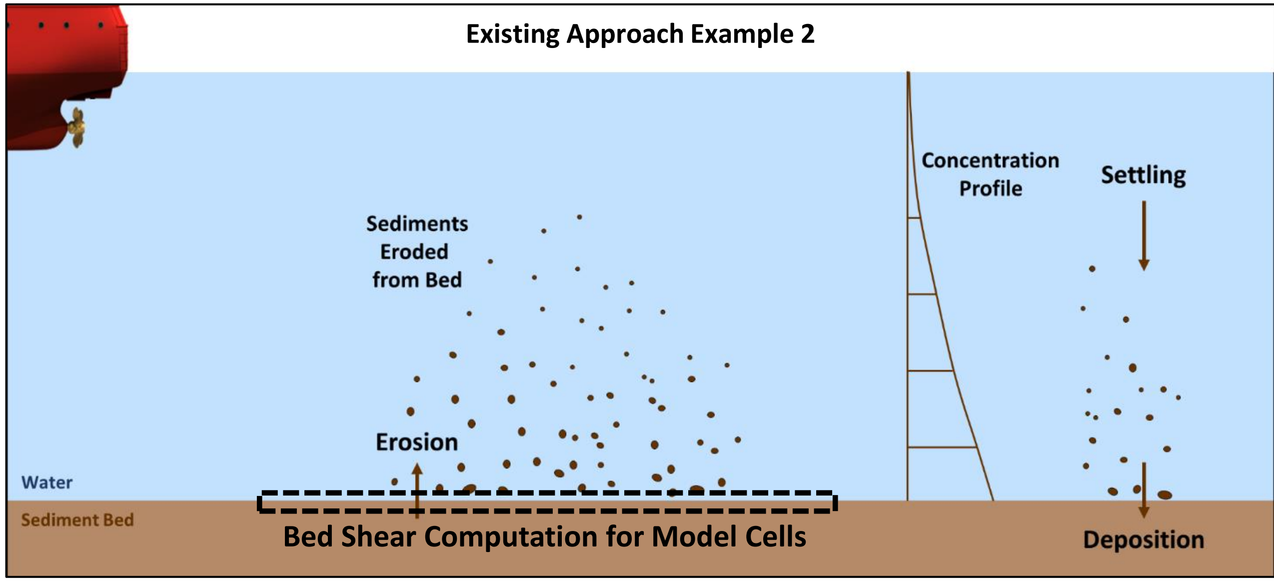
- Propeller wash (propwash) can cause resuspension and redistribution of sediment bed materials, which may significantly influence aquatic ecosystems in areas with high vessel traffic (i.e., ports, harbors, navigation channels, and locks).



Background

- Over the years, several approaches have been proposed to predict the propwash-induced redistribution of sediments using computational modeling tools.
- However, the existing ways have mostly been limited to providing uncoupled representations of hydrodynamics, sediment transport, and the propwash effects.
  - Manually estimated the mass of resuspended sediments, then used the estimated mass as a source term model input for the transport simulation of existing modeling tools (Wang et al., 2016).
  - Revised the computer codes of modeling tools to implement the ship-generated bed shear stress at a model cell resolution for the sediment resuspension calculation (Hammack et al. 2008; Hayter et al. 2016; Poon et al. 2016; Ziegler et al. 2019).





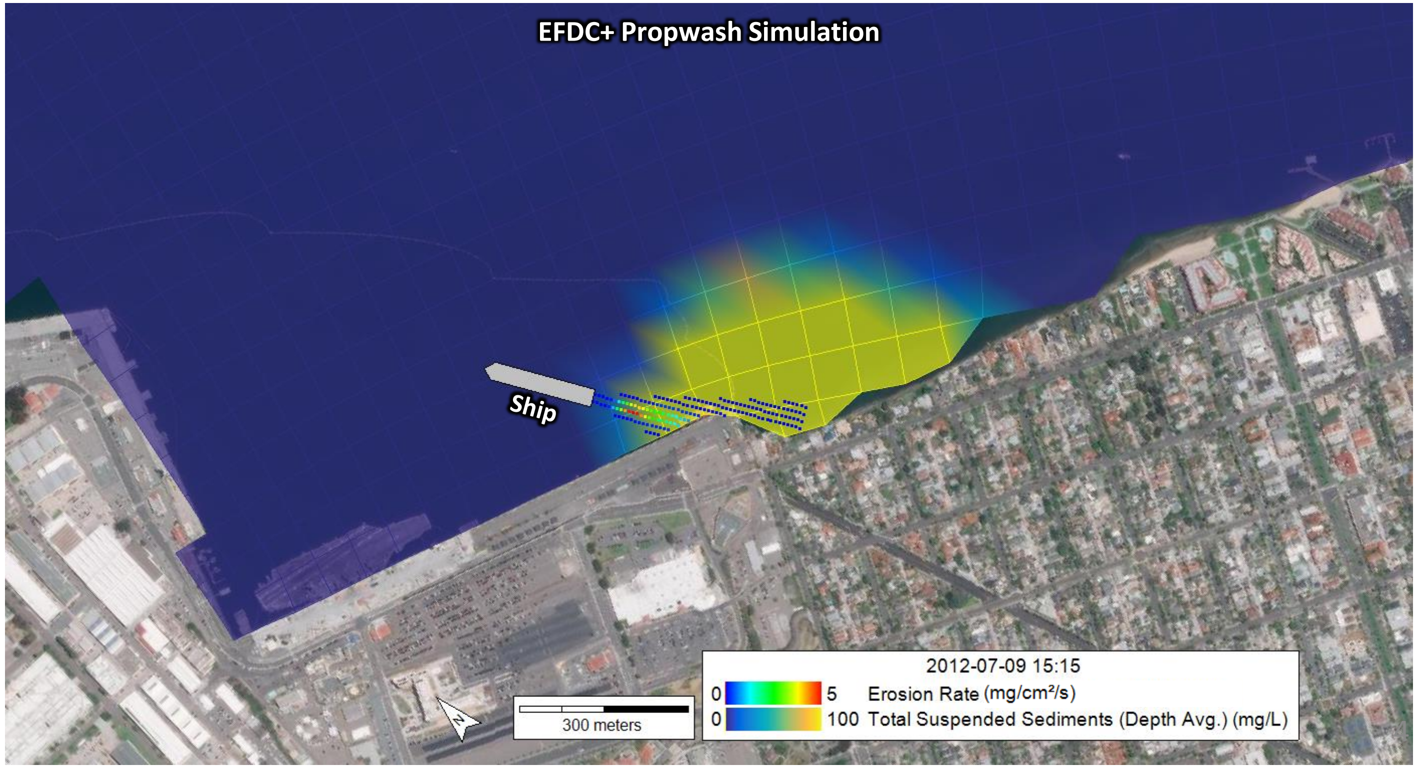
Propwash Modeling with EFDC+

Goal: Develop a modeling method to implement <u>a dynamically linked simulation</u> of hydrodynamics, sediment transport, and propwash resulting from ship traffic.

- Integrate analytical solutions of propwash-driven flow velocity and shear stress into the numerical algorithm of Environmental Fluid Dynamics Code Plus (EFDC+).
- Use Automatic Identification System (AIS) ship traffic data as model inputs.

<u>With the EFDC+ propwash method,</u> a single model run can simulate combinations of:

- Bed erosion;
- Sediment resuspension;
- Subsequent movements of the resuspended sediments in the water; and
- Deposition in the sediment bed;



Algorithmic Implementation for Propwash Modeling

Dynamically Couple the Propwash Effects

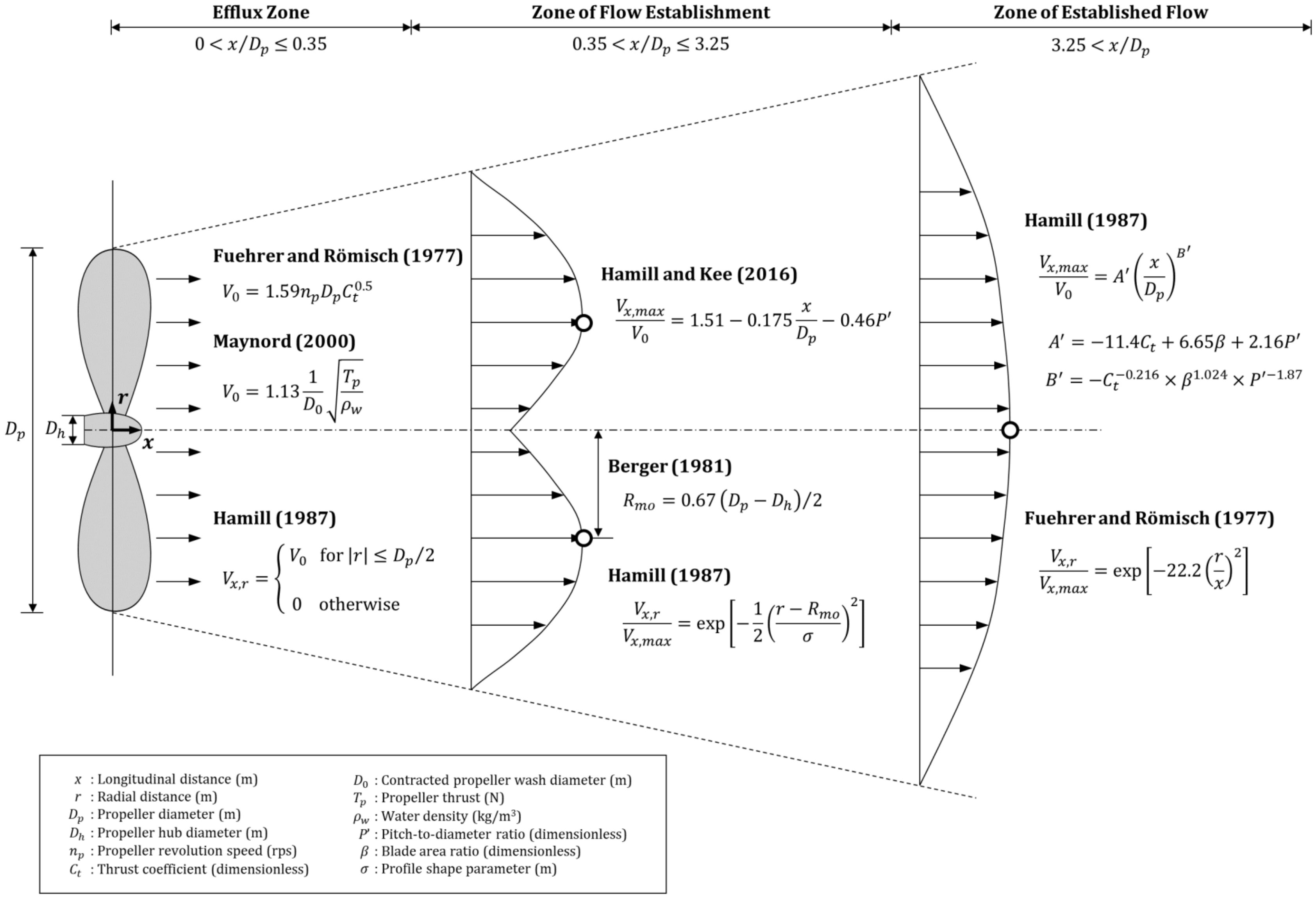
to EFDC+ Hydrodynamic and Sediment Transport

Analytical Solutions for Propwash Velocity

- Propwash formation and diffusion processes differ explicitly among three zones behind a rotating propeller.

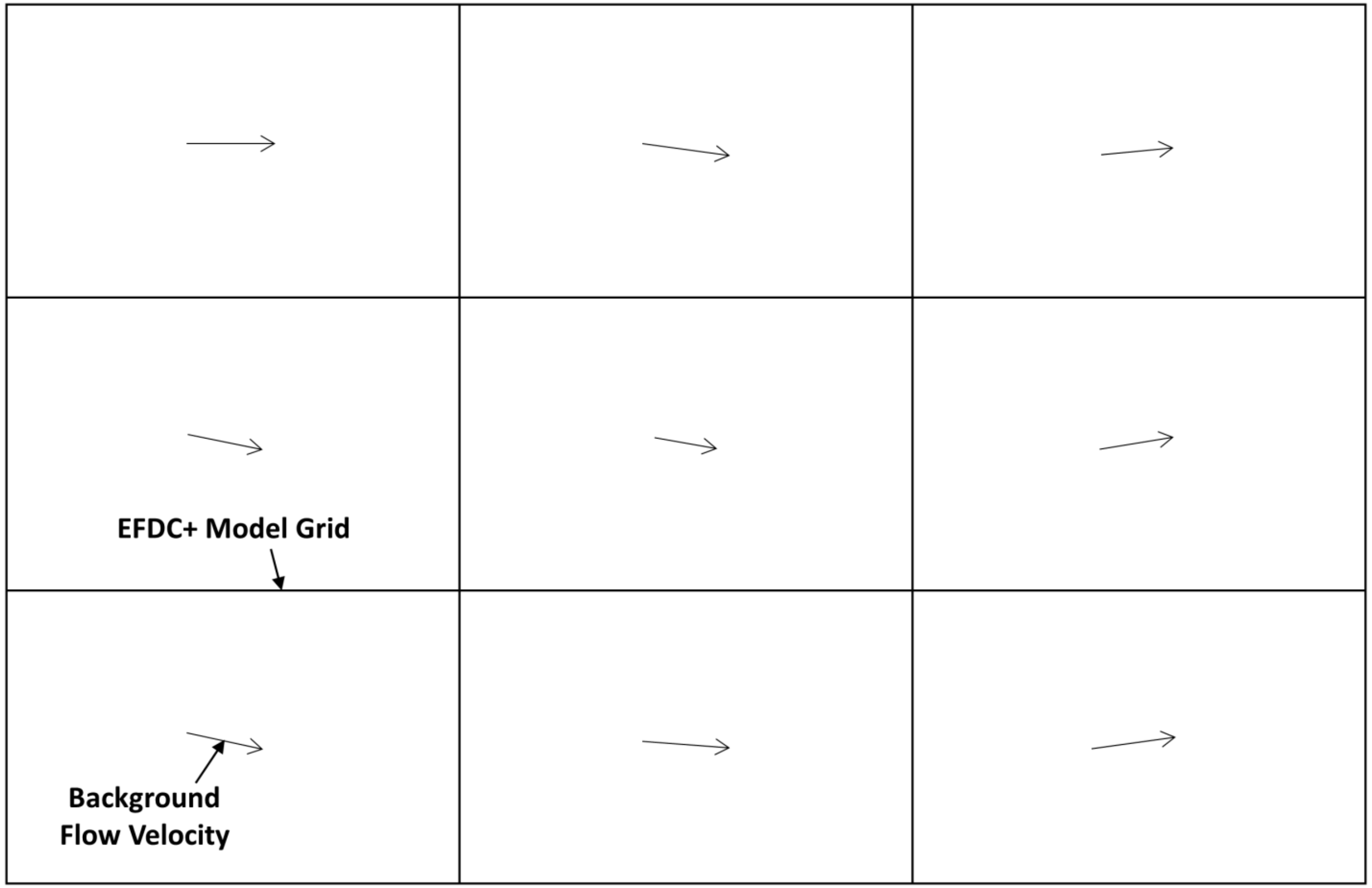
- Empirical velocity equations have been suggested to represent a three-dimensional propwash velocity field.

- <u>This study</u> uses these equations in the propwash modeling algorithm to:
  - Compute erosion rate at the water-sediment interface.
  - Calculate flow momentum flux in the water column; and



General EFDC+ Algorithmic Implementation

Plan View



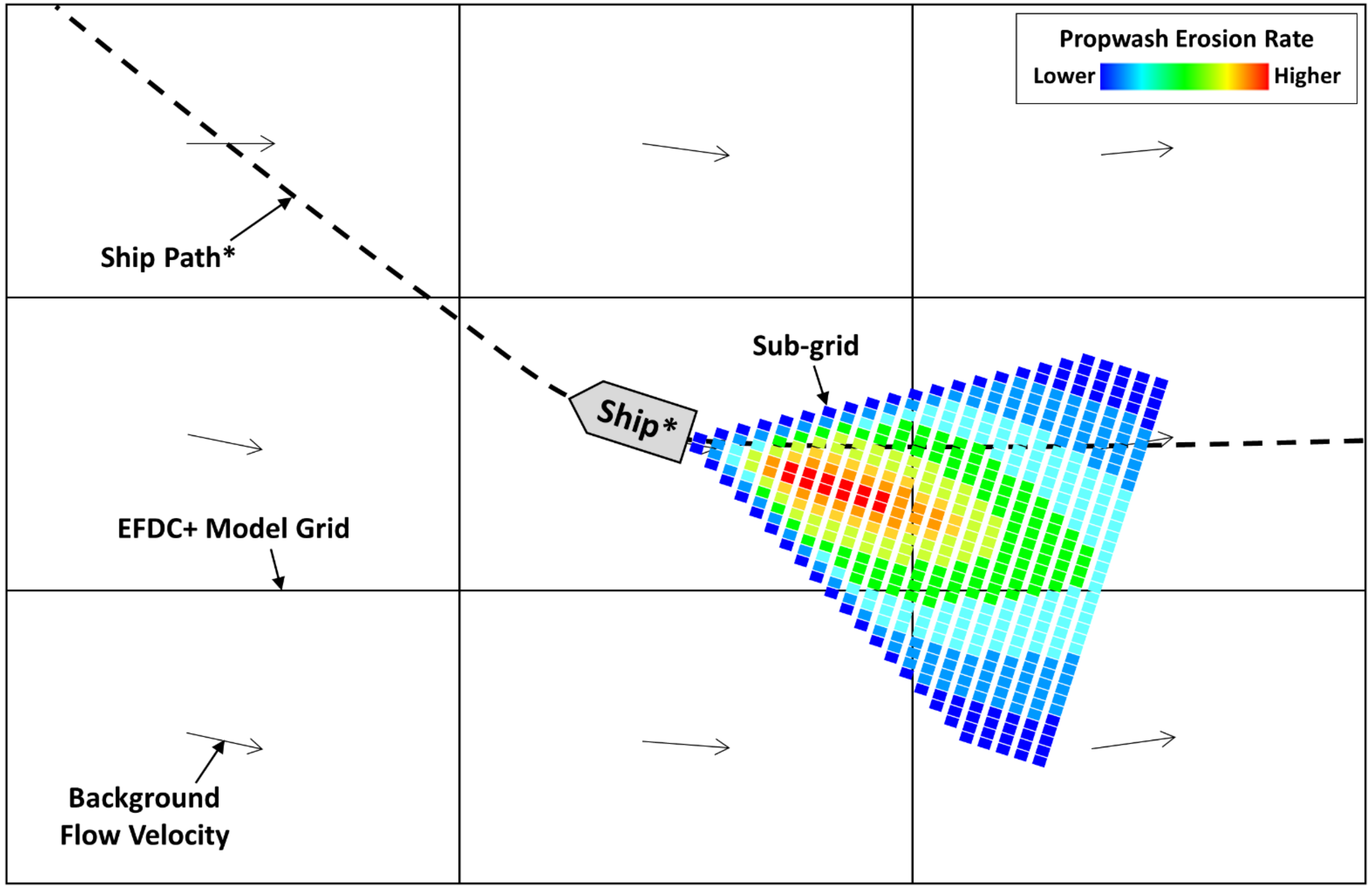
In a general model simulation of EFDC+,
3D hydrodynamics and sediment transport processes are computed at a model grid cell resolution.

For every computation time step, each cell has:

- Bottom elevation
- Water depth
- Flow velocity of water
- Sediment and chemical concentrations in the water
- Sediment and chemical mass in the sediment bed
- And many other parameters

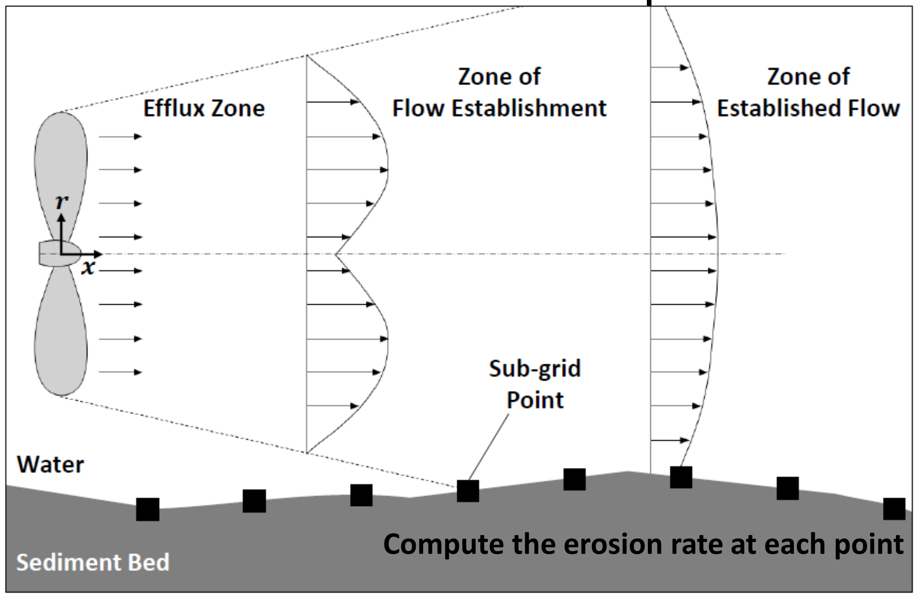
Propwash Implementation

Plan View

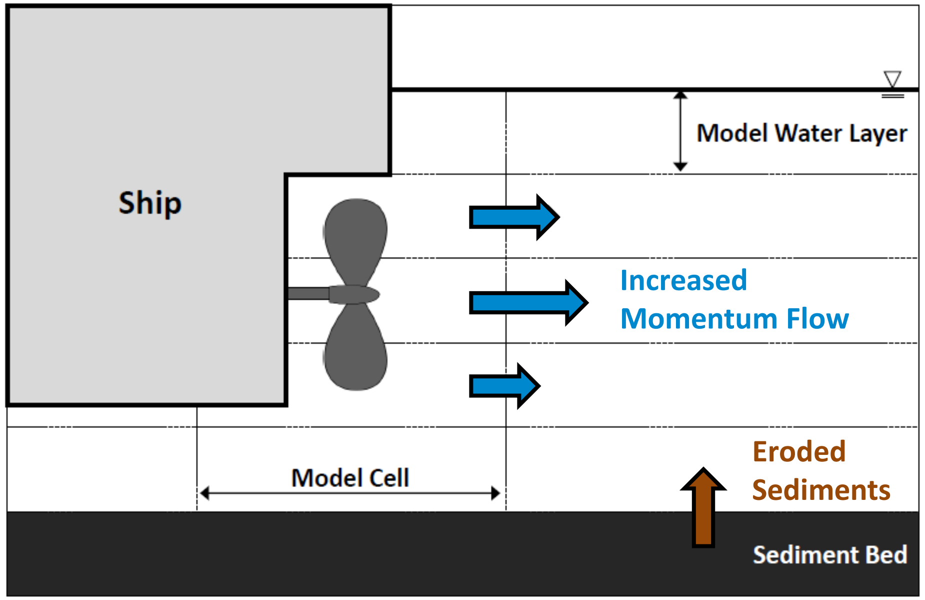


* Ship path and ship properties are the essential model inputs for propwash simulation.

Side View for Erosion Rate Computation

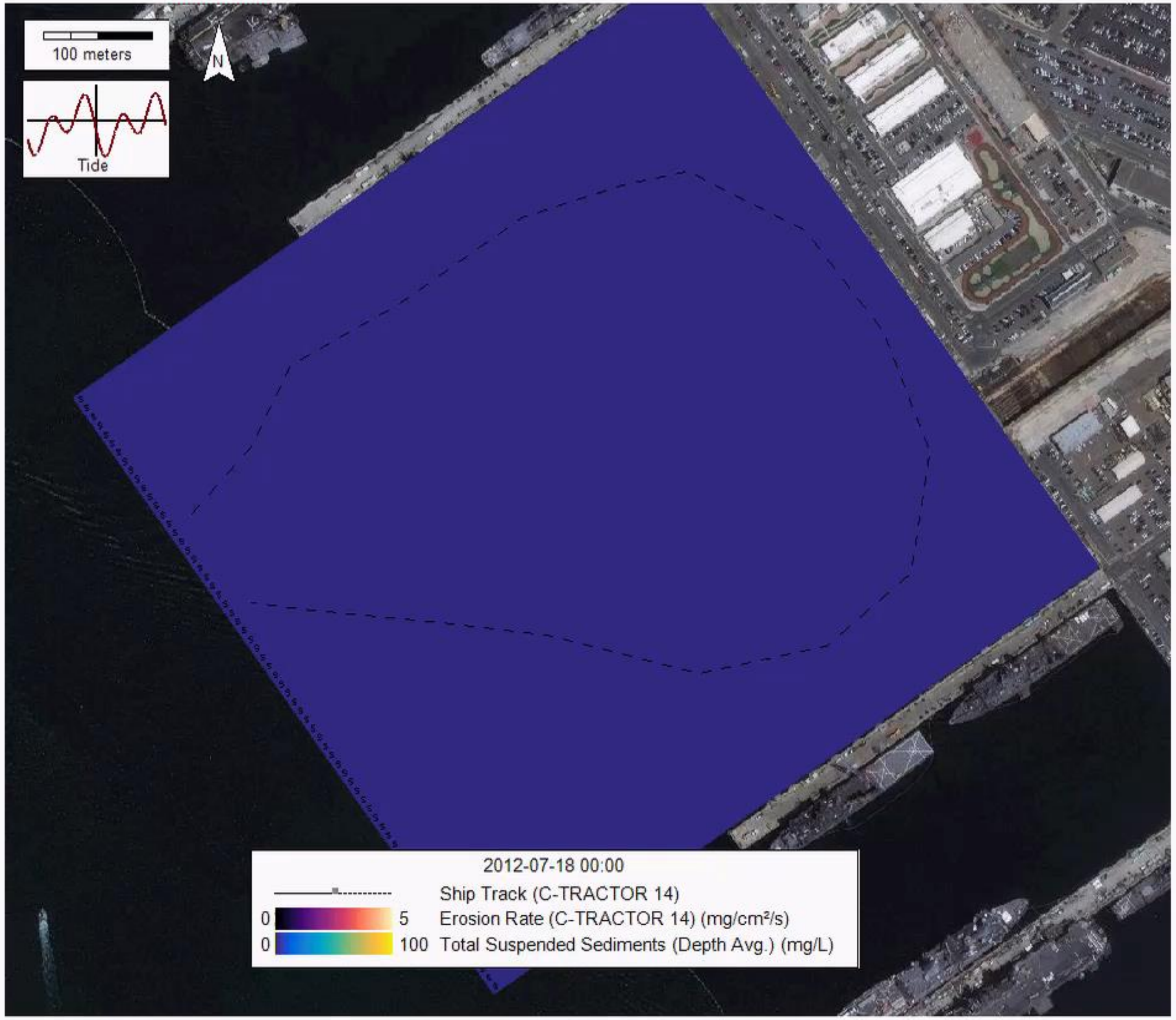


Side View for Flow Momentum Computation

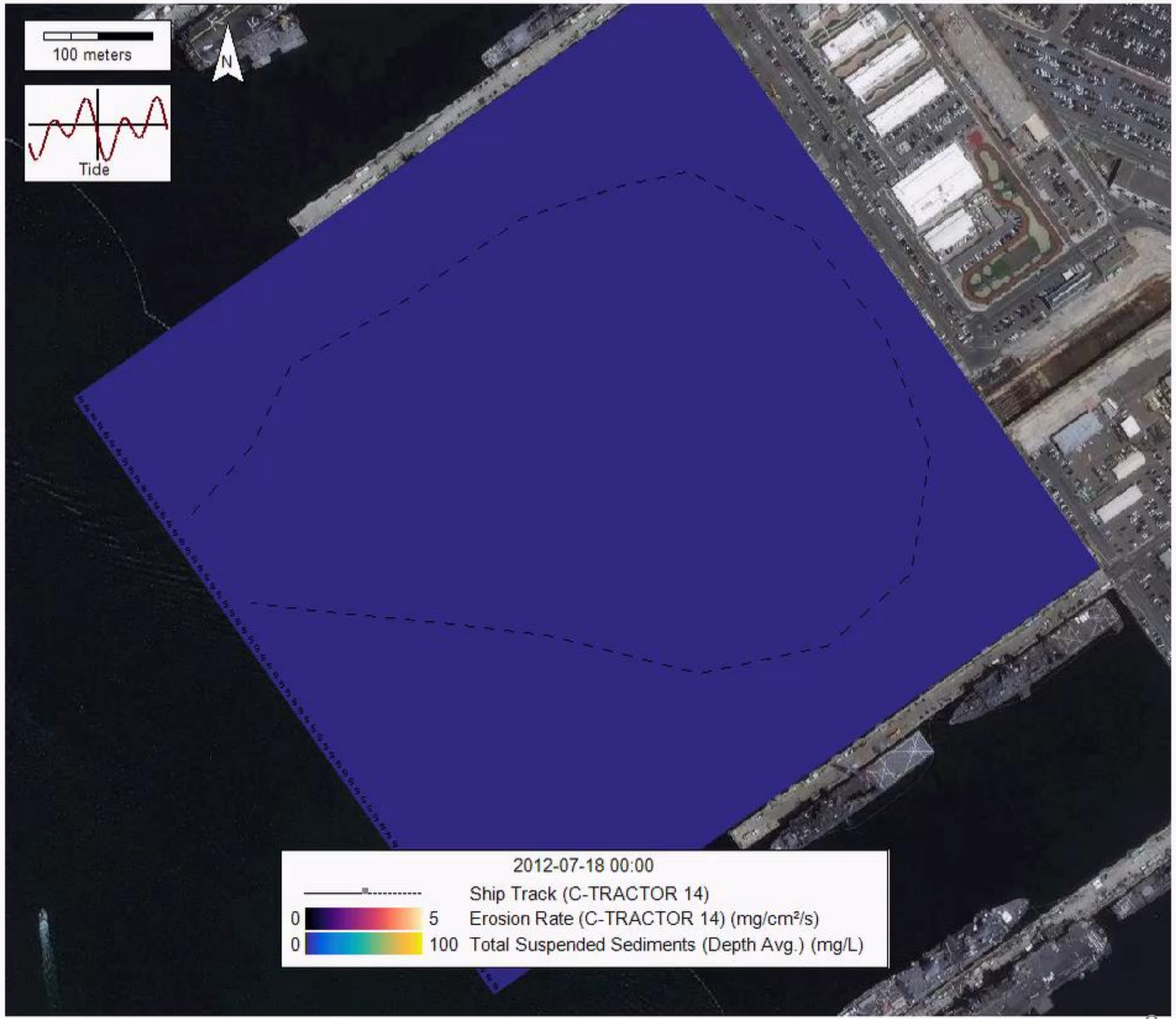


Demonstration With Example Ship Transit

Simulation With Propwash Momentum Effect



Simulation Without Propwash Momentum Effect

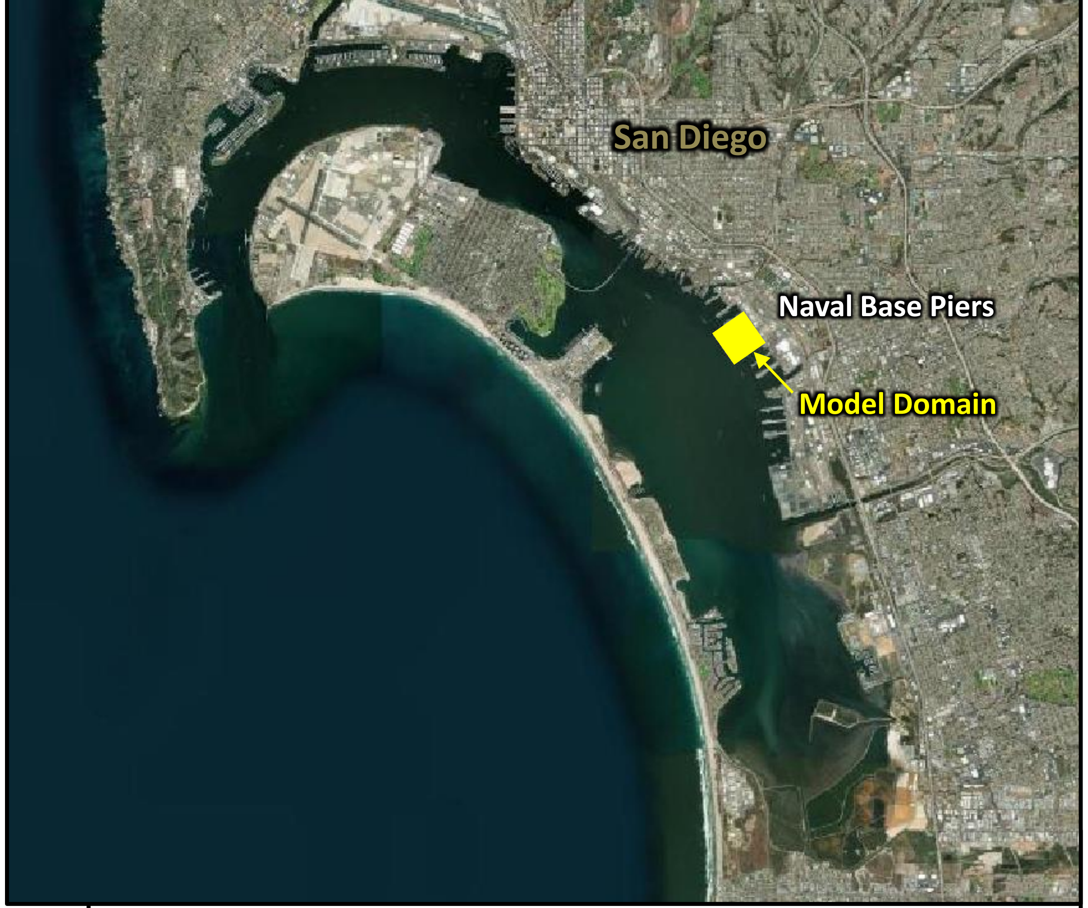


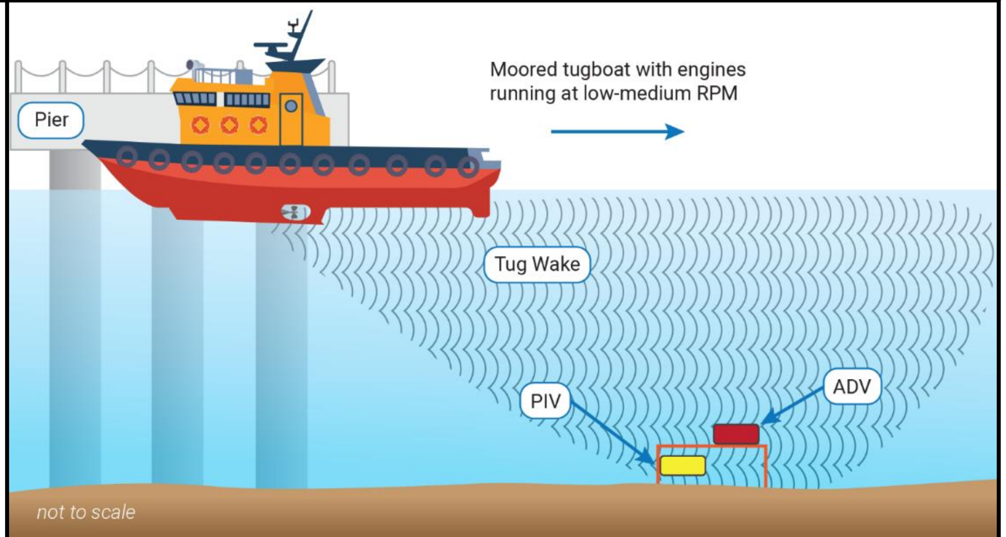
Model Validation with US Navy Field Test Cases

Small-scale Model of San Diego Bay Naval Base Piers

US Navy Field Test #1

- Location: San Diego Bay Naval Base Piers
- Survey Date: July 19th, 2012
- Tugboat Tractor C-14 moored at the dock
- Changing propeller revolution speeds consecutively
  - 20 rpm for 7 min;
  - 50 rpm for 11 min;
  - 100 rpm for 9 min;
  - 150 rpm for 9 min; then
  - Engine stop.
- **Measurements 110 m behind the tugboat**
  - Near-bed flow velocity using Acoustic Doppler Velocimetry (ADV)
  - Bed elevation changes using Particle Image Velocimetry (PIV) images

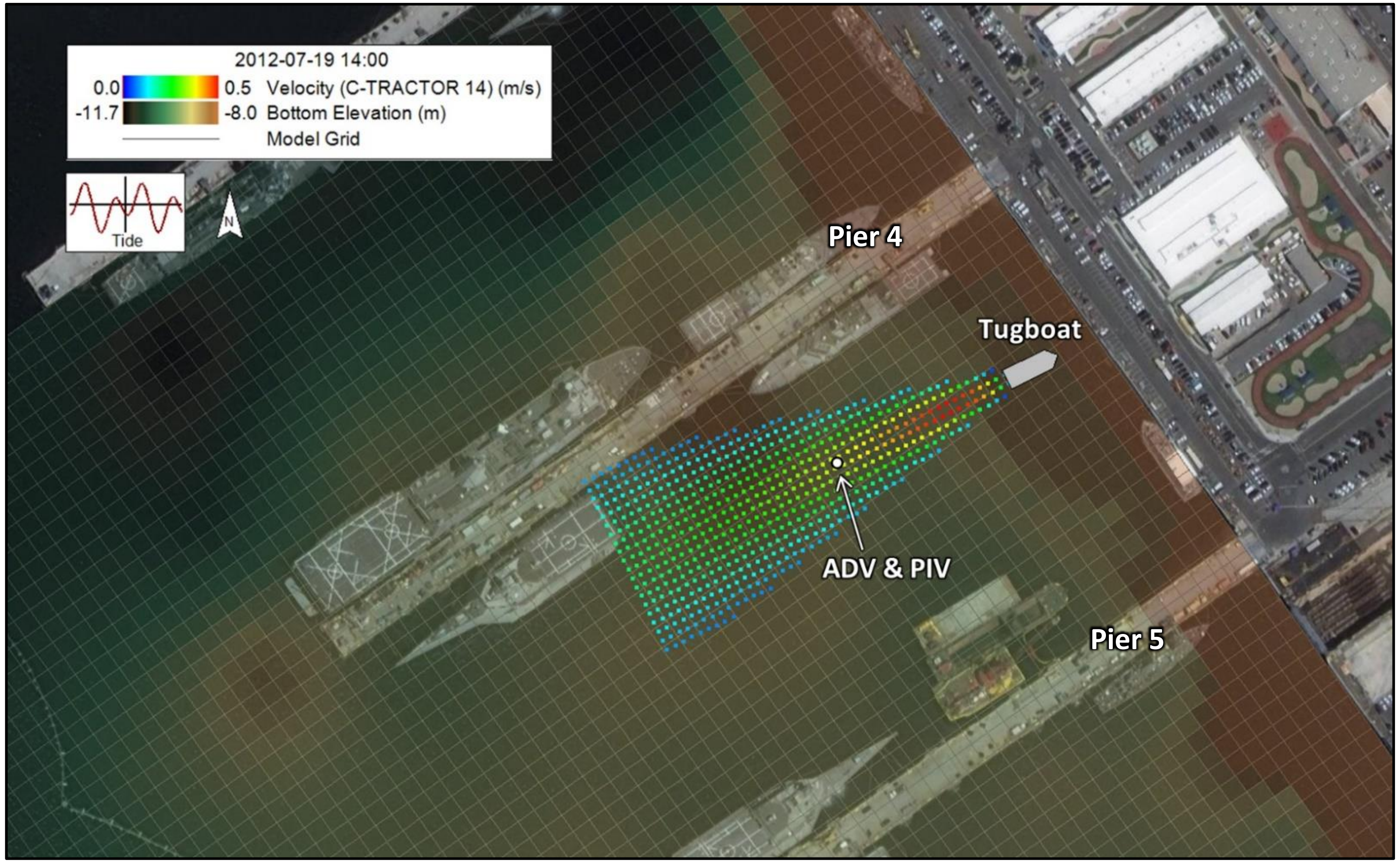




Model Development

- Model Grid
  - 4,556 Uniform horizontal cells (10 m x 10 m)
  - 10 Vertical water layers
- Hydrodynamics
  - Mean water depth = 9.14 m
  - Tidal conditions at open boundaries
- Sediment Bed
  - 60% clay, 20% silt, 20% sand
- Propeller Wash: Tractor C-14
  - Moored at a fixed location
  - Length: 28.6 m, Breadth: 10.4 m, Draft: 4.8 m
  - Two ducted propellers, Diameter: 2.28 m
  - Set the propeller revolution speeds to vary the same as the field test

Model Conditions for San Diego Bay Field Test Case



Model Calibration: Near-Bed Flow Velocity

- **ADV-measured Flow Velocity**

  Considered average and standard deviation of the flow velocities for each rpm period

- **Hydrodynamic Parameter Calibration**

  Horizontal eddy viscosity: 3 x 10^{-3} m^2/s

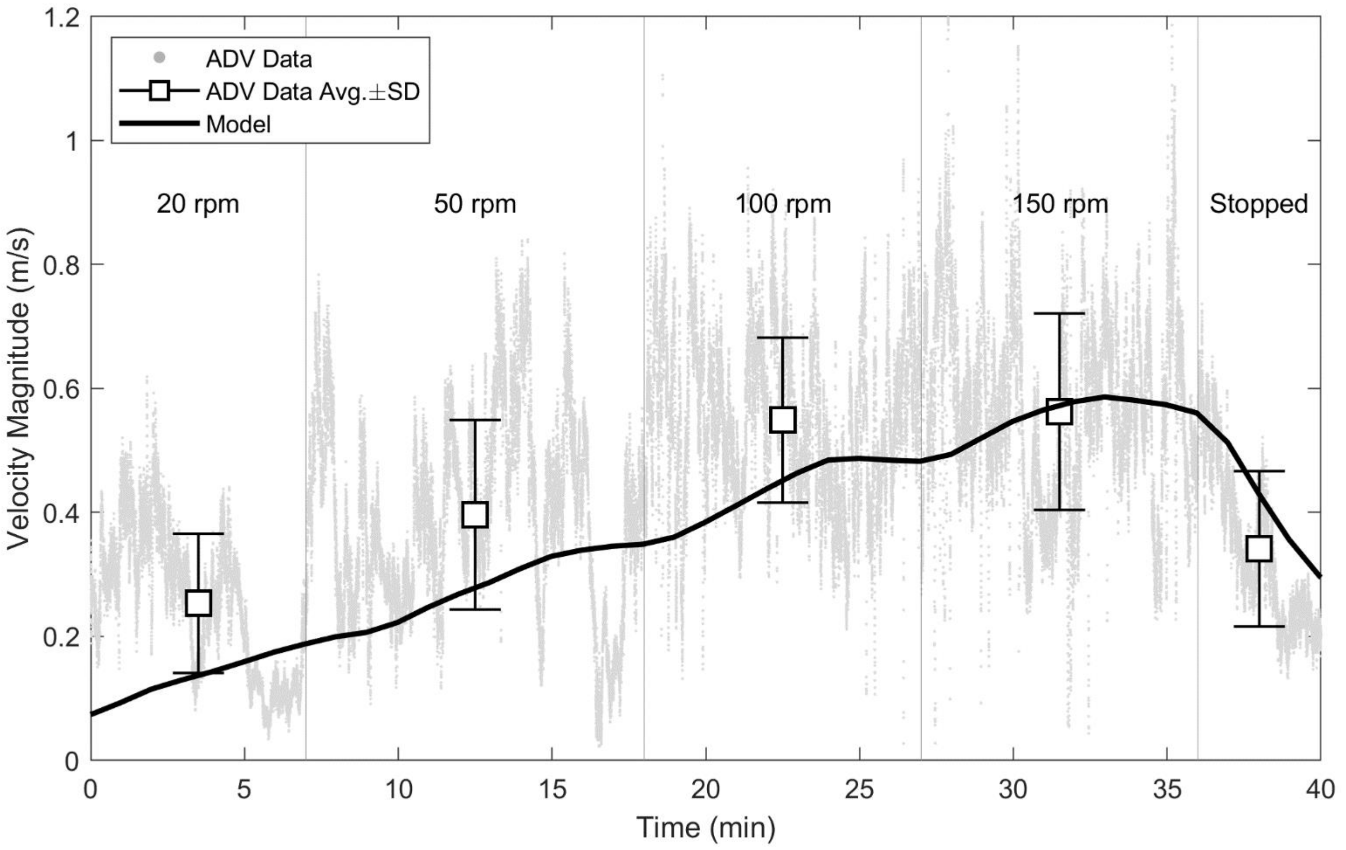
  Vertical eddy viscosity: 1 x 10^{-5} m^2/s

  Momentum Effect Factor f_p: 0.5

Arithmetic average flow velocities (m/s) for each rpm period

	20 rpm	50 rpm	100 rpm	150 rpm	Stop
Data	0.25	0.39	0.53	0.57	0.34
Model	0.14	0.28	0.44	0.56	0.40

Propwash velocity from ADV data and model results

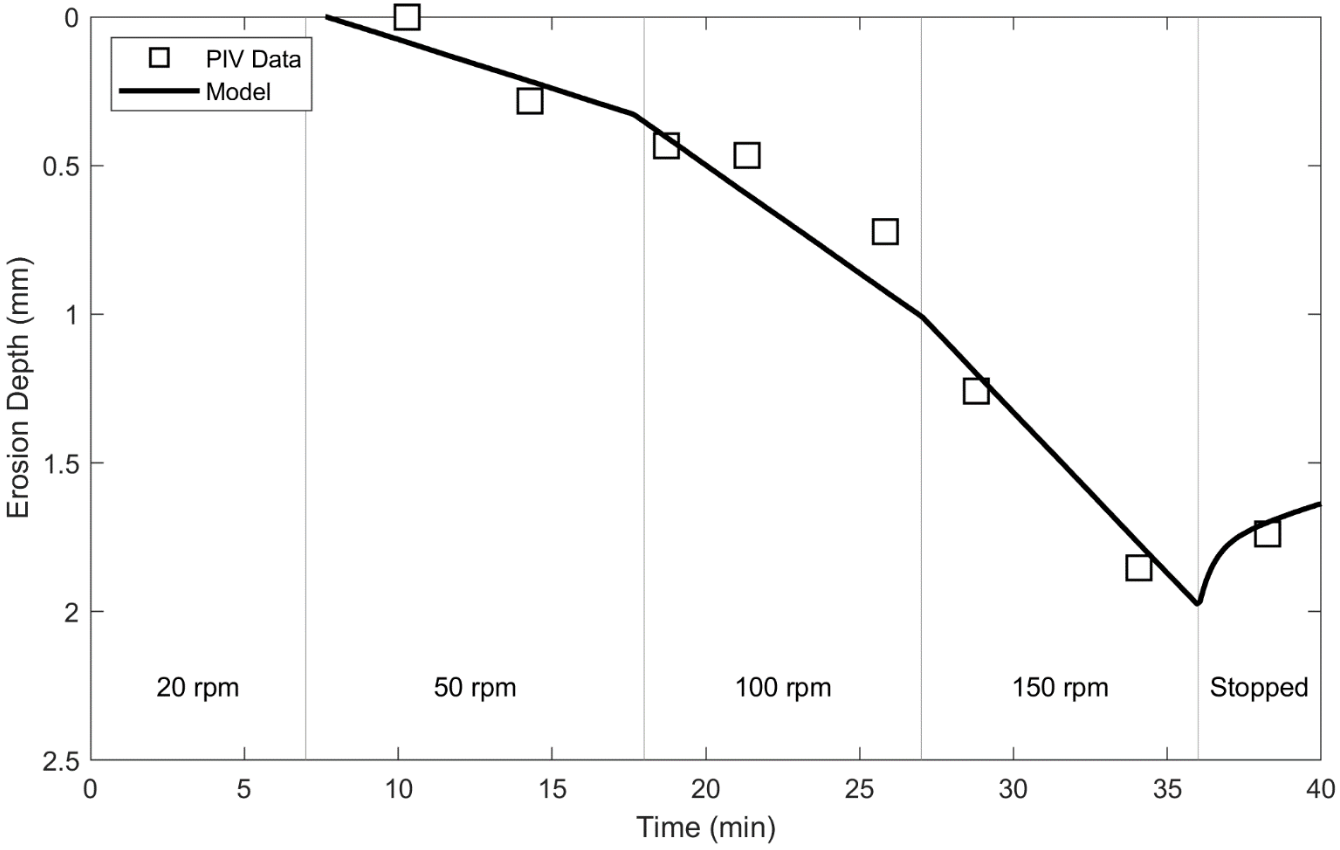


Model Calibration: Erosion Depth

- **PIV-measured Erosion Depth**
  - Reached 1.85 mm at 34 min
  - Showed re-deposition once the propellers were brought to a stop

- **Sediment Model Calibration**
  - Erosion rate parameters: A = 1.6 x 10^{-4} , n = 1
  - Reached 1.82 mm erosion at 34 min
  - Reproduced the deposition of the suspended sediments in the stop period
  - Indicated **Nash-Sutcliff Efficiency (NSE)* of 0.98** for model performance

Erosion depth from PIV-measured data and model results

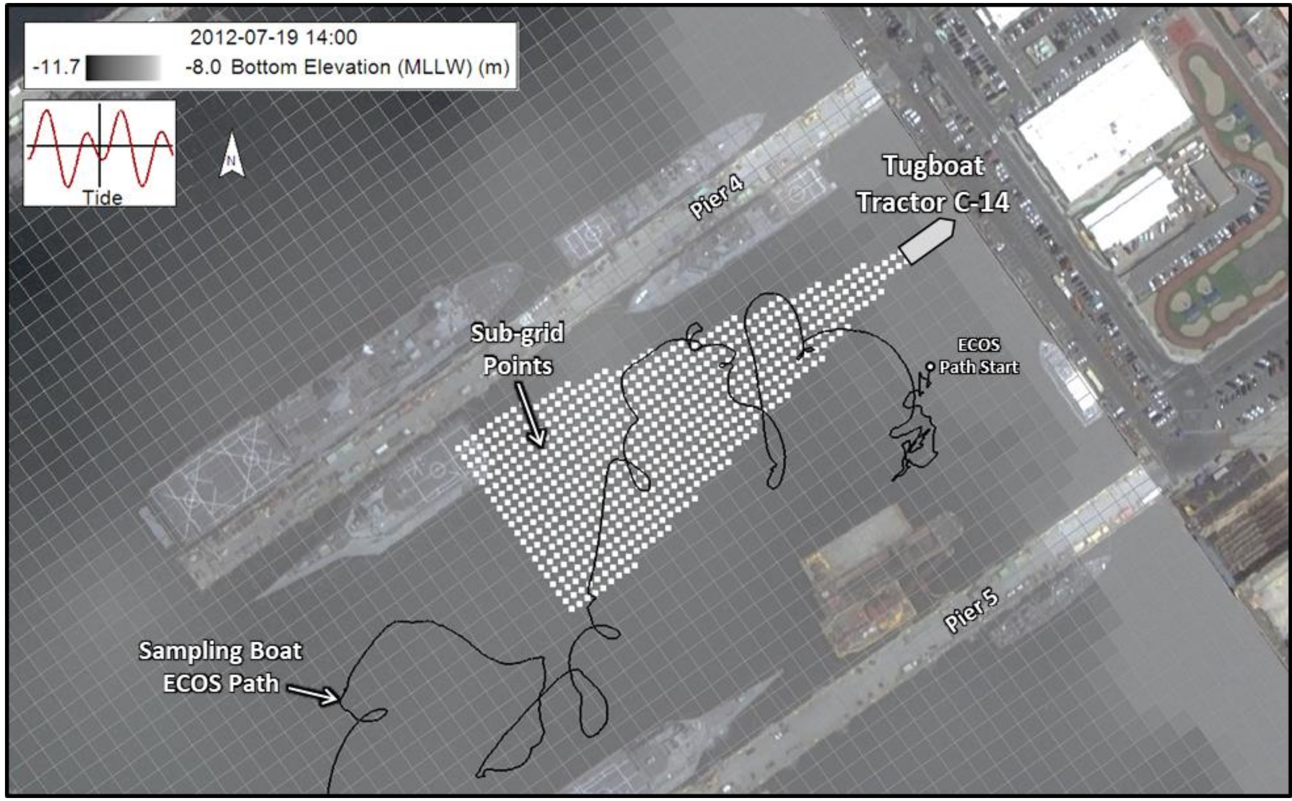


* The NSE can range from -∞ to 1 where NSE of 1 indicates that the model reproduces the observed data perfectly

US Navy Field Test #2 in San Diego Bay

- Survey Date: April 4th, 2012
- Used Tractor C-14 at the same location as Test #1
- Propeller revolution speeds
  - 20 rpm for 5 min
  - 50 rpm for 5 min
  - 100 rpm for 5 min
  - 150 rpm for 5 min
  - Engine stop
- **Collected water samples in and around the tugboat-induced plume to measure <u>Total Suspended Sediment (TSS) concentrations</u>**

  (The measured minimum was 3.5 mg/L)



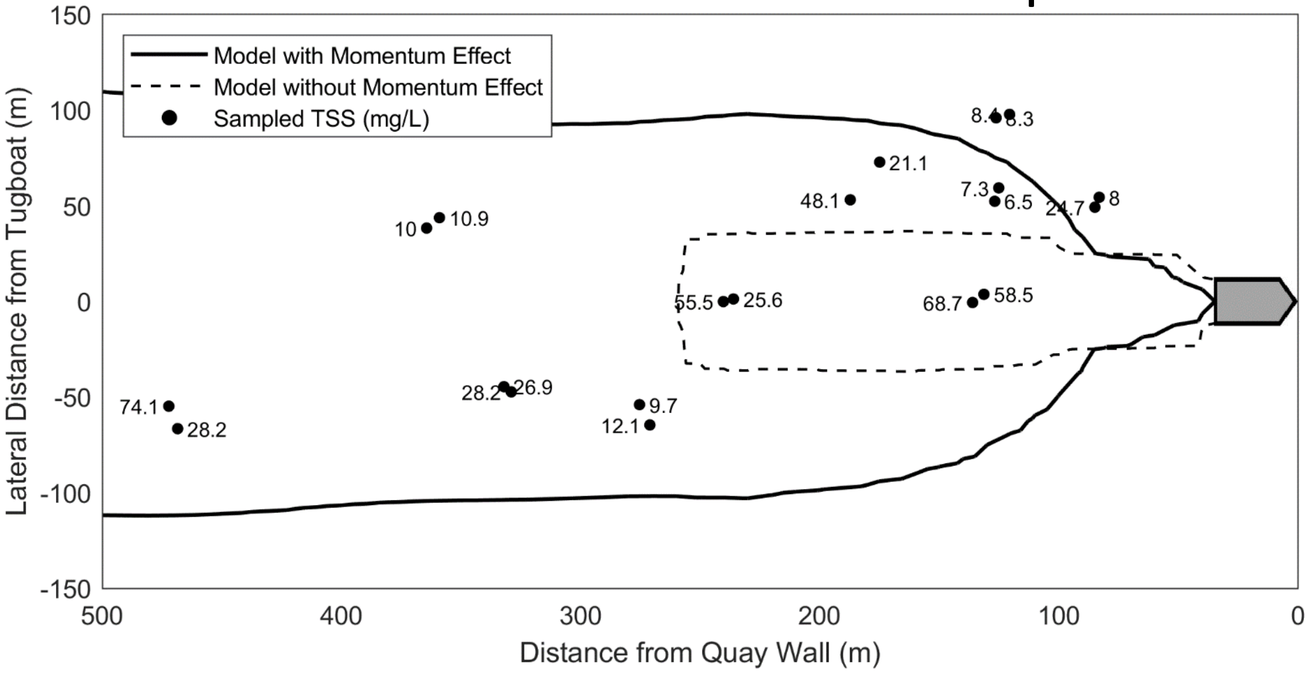
Path of TSS Sampling Boat

*All model parameters specified from the model calibration were applied to the model validation run

Model Validation: Plume Extent & TSS Concentrations

- The modeled sediment plume extent covered most locations where the sampling boat observed the plume.
- The model reasonably reproduced the measured TSS concentration range of the water samples.
- More dispersion of resuspended sediments was simulated when the propwash momentum effect was linked to the hydrodynamic flow field computation.

Modeled Sediment Plume Extent and ECOS Sample Location



Measured and Modeled TSS Concentrations (mg/L)

	Min.	Avg.	Max.
Data	3.5	19.3	74.1
Model	3.5	15.7	72.5

Application to San Diego Bay Ship Traffic

Full-scale Model of San Diego Bay

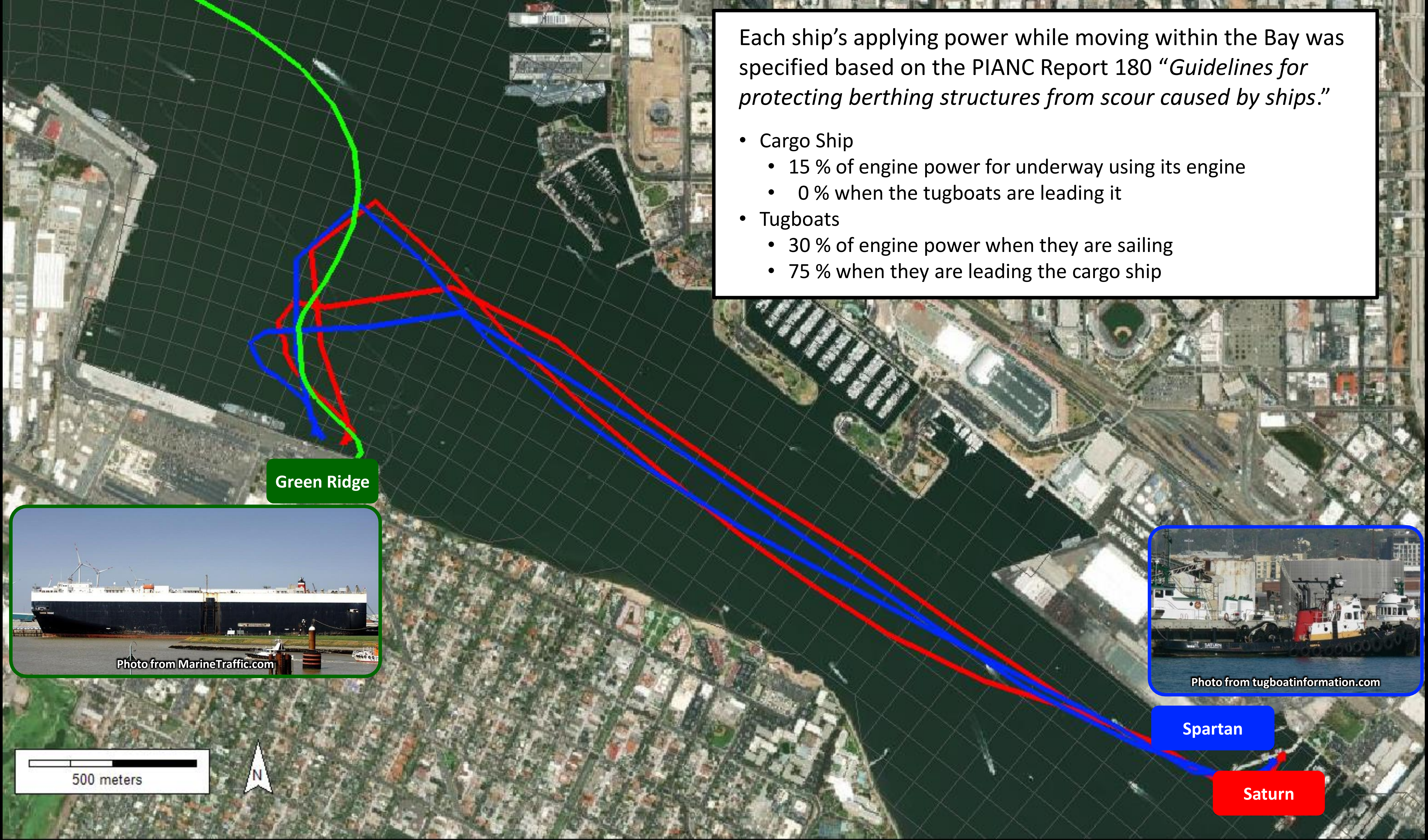
Model Development

- A departure of a cargo ship being helped by twin tugboats on July 9th, 2012
- Hydrodynamics & Sediment Bed
  - 7,615 Horizontal cells (Avg cell size: 150 m x 120 m)
  - Mean water depth for navigation channel = 14 m
  - 65% fines, 32% fine sand, 3% coarse sand
- Propeller Wash
  - Collected AIS ship traffic data from Marine Cadastre
  - Selected three ships to be modeled

	Green Ridge	Saturn & Spartan
Type	Cargo	Tug
Length	200 m	28 m
Beam	32 m	9 m
Draft	9 m	4 m
Engine Power	16,500 hp	3,500 hp
# of Propellers	2	2
Propeller Diameter	3.98 m	2.5 m

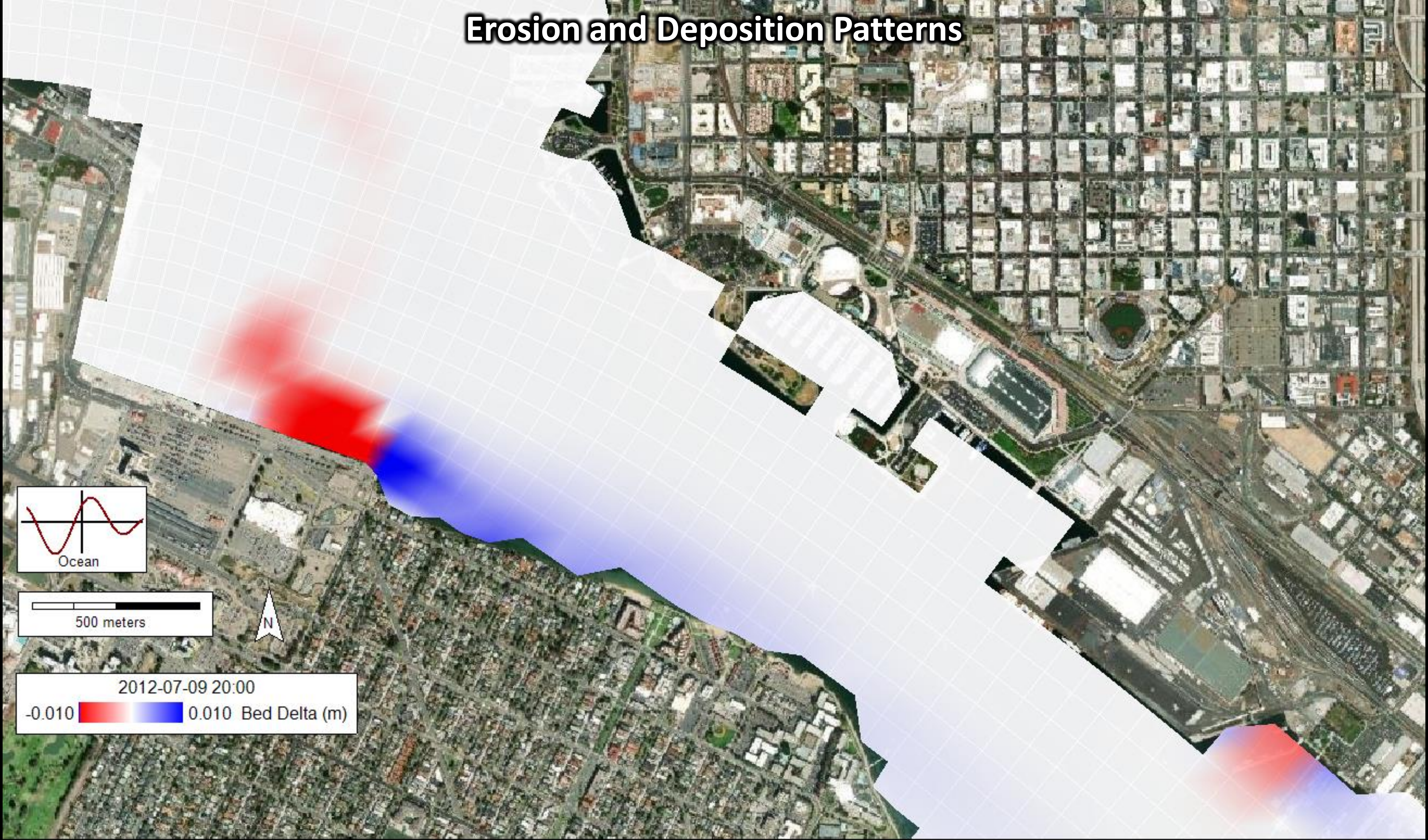
Each ship's applying power while moving within the Bay was specified based on the PIANC Report 180 "*Guidelines for protecting berthing structures from scour caused by ships.*"

- Cargo Ship
  - 15 % of engine power for underway using its engine
  - 0 % when the tugboats are leading it
- Tugboats
  - 30 % of engine power when they are sailing
  - 75 % when they are leading the cargo ship



Suspended Sediments Resulting From Ship Traffic

Erosion and Deposition Patterns



Conclusion

- This study offered a modeling tool that can implement a fully linked simulation of hydrodynamics, sediment transport, and propwash resulting from ship traffic:
    - Bed erosion;
    - Sediment resuspension;
    - Advection and dispersion of the resuspended sediments in the water; and
    - Deposition in the sediment bed;

- **EFDC+ propwash modeling tool will be beneficial for researchers, engineers, and regulators in their efforts to establish a sound foundation for:**
    - ***Contaminant remediation planning;***
    - ***Engineered channel design; and***
    - ***Long-term port management.***

Thank You

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