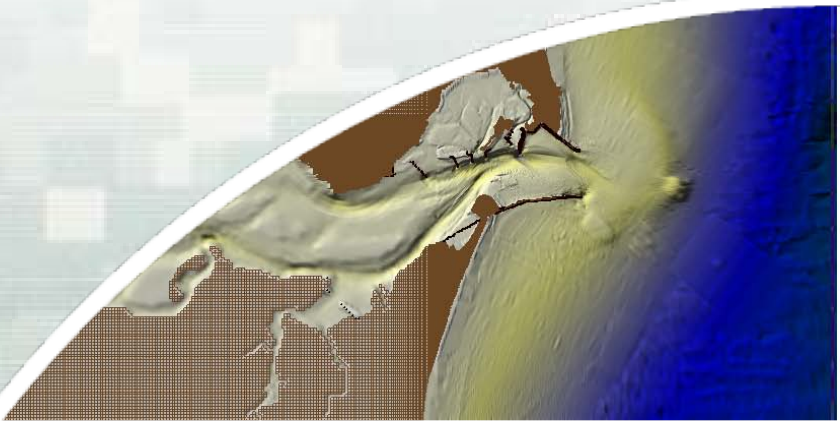
Coastal Modeling System

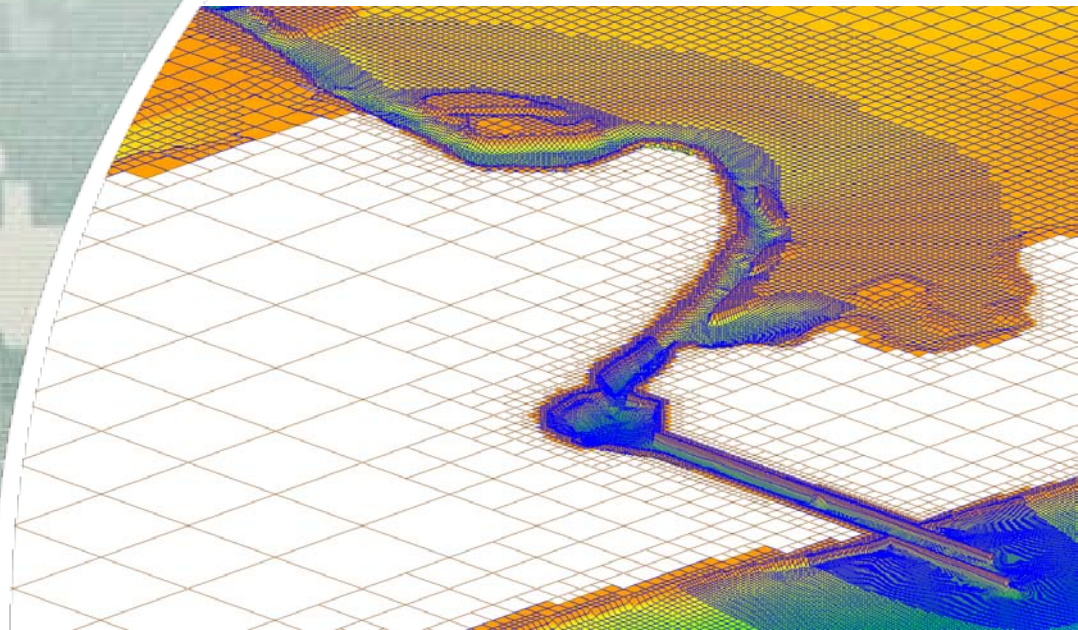
Overview, background and capabilities

Alex Sánchez, and CIRP team
Research Hydraulic Engineer
Coastal and Hydraulics Laboratory
Engineer Research and Development Center
May 20, 2010

Weiming Wu
National Center for Computational
Hydroscience and Engineering
University of Mississippi, MS

Chris Reed
URS Corporation
Tallahassee, FL

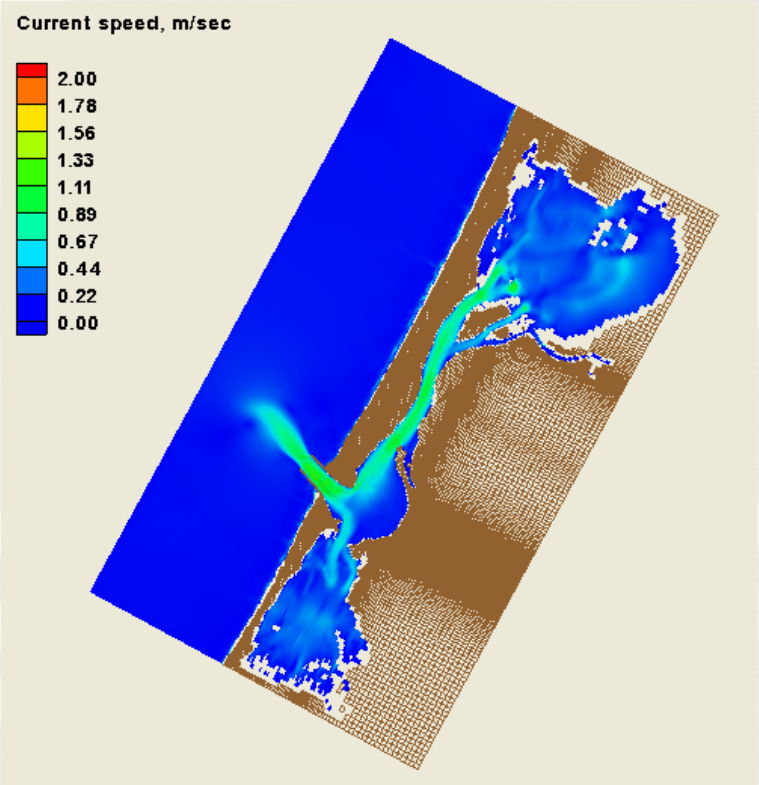




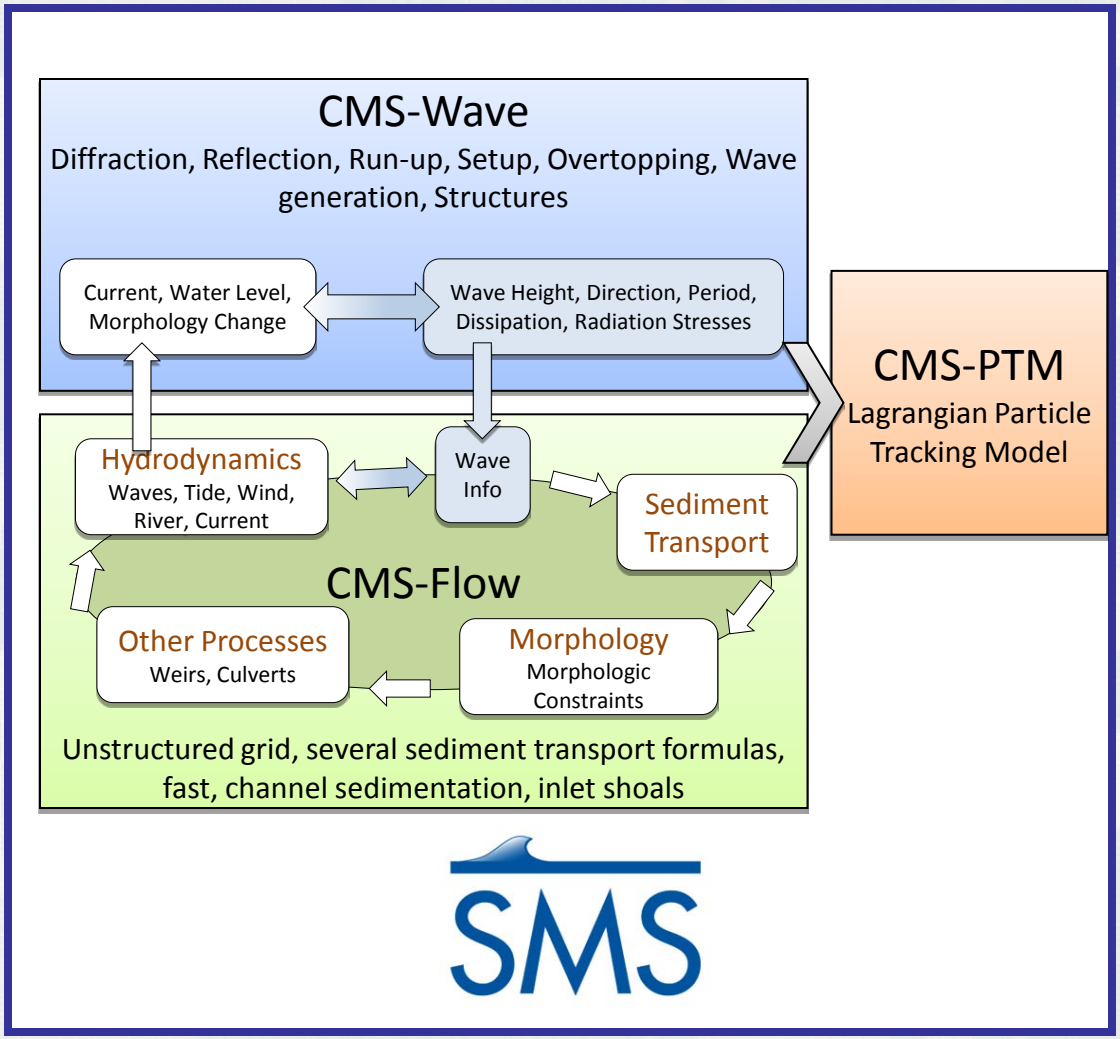
US Army Corps of Engineers
BUILDING STRONG®

Outline

- CMS Overview
- Hydrodynamics
- Waves
- Sediment transport
- Example applications
- Questions



CMS Overview



Since 1997…

- 32 workshops
- Districts can independently run the CMS!

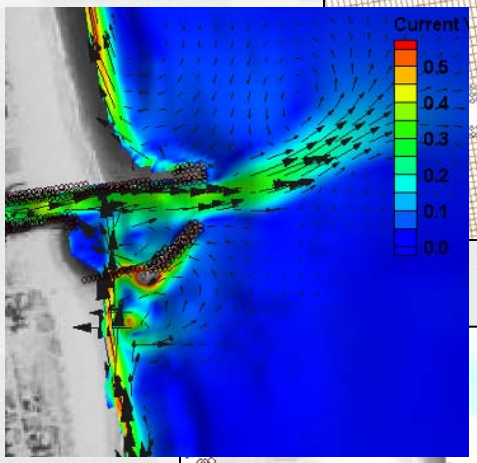
Advantages…

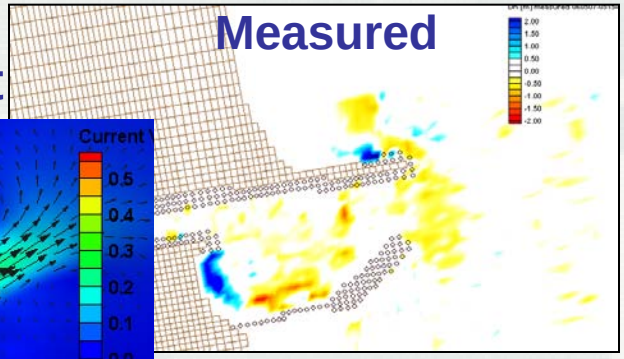
- Robust
- Physics-based
- Integrated SYSTEM
- In SMS
- User-friendly

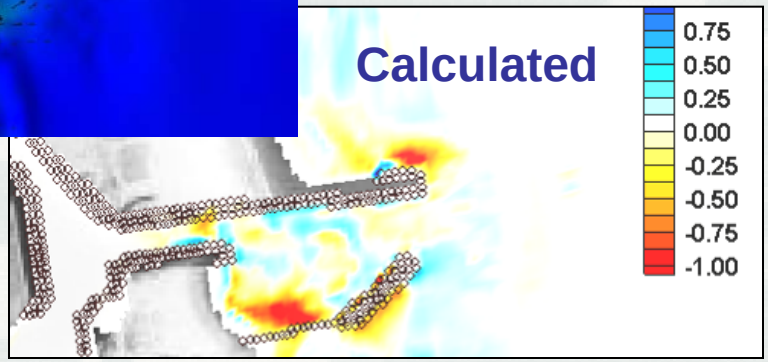
CMS-Flow Key Features

- Finite Volume Method
  - Conserves mass
  - Stable
  - Accessible
- Coupled with spectral wave model (CMS-Wave)
  - Wave-current interactions
- Inline sediment transport and morphology change
- Nesting capability
- Tide, river, wind, atm. pres., etc.
- Integrated Particle Tracking Model (CMS-PTM)
- User friendly interface and
- XMDF I/O

Wave & Tide driven current

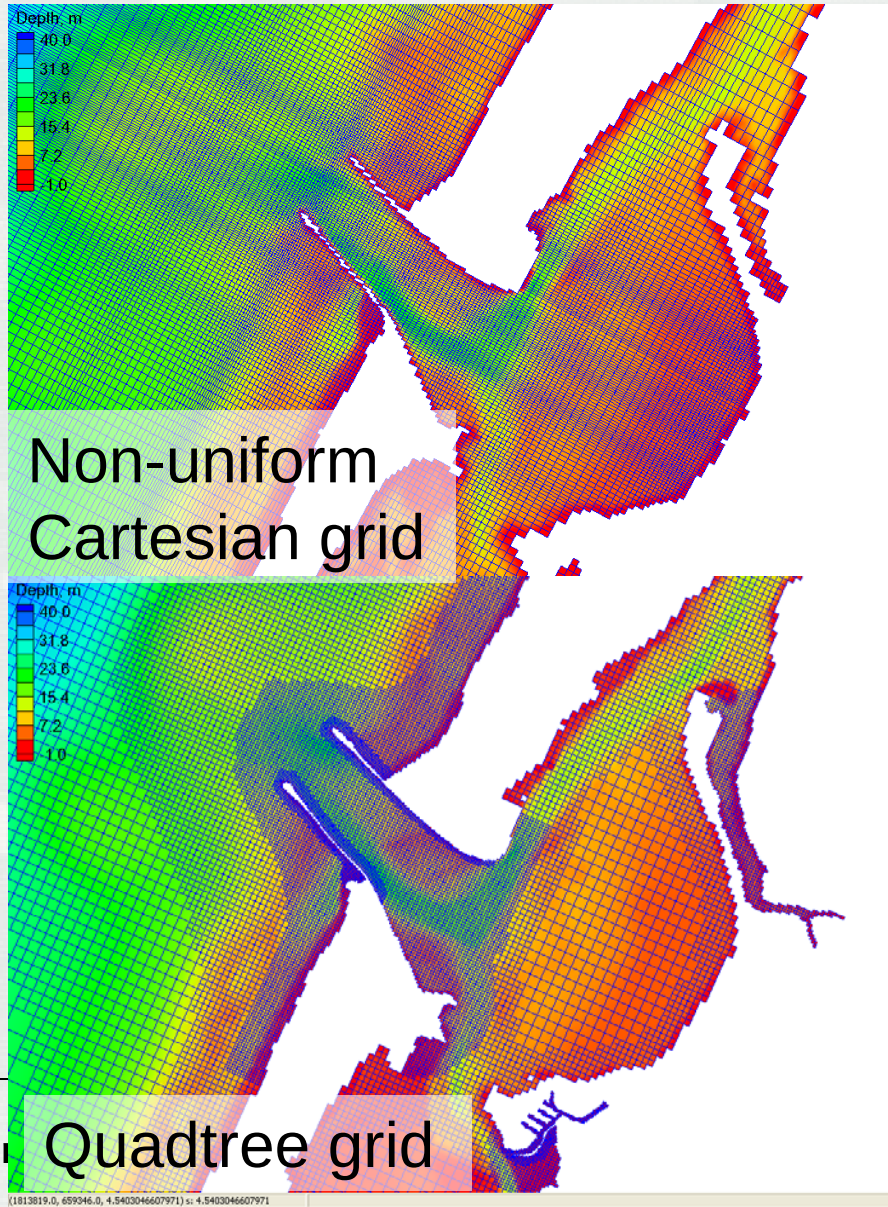






CMS-Flow Key Features

- Grid options
  - Non-uniform Cartesian grid: Easy to setup
  - Telescoping (quadtree) grid: Efficient, flexible
- Solver options
  - Implicit: Tidal flow, long-term morphology change. ~10 min time step
  - Explicit: Flooding, breaching, super-critical flow. ~ 1 sec time step
- Parallel Processing



Hydrodynamics

Conservative form of the depth-averaged shallow water equations in Cartesian coordinates

$$\frac{\partial h}{\partial t}+\frac{\partial (hu_j)}{\partial x_j}=S,\quad j=1,2 \qquad h=\zeta+\eta$$

$$\frac{\partial (hu_i)}{\partial t}+\frac{\partial (hu_iu_j)}{\partial x_j}-\varepsilon_{ij3}f_c u_j h=-gh\frac{\partial \eta}{\partial x_j}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\nu_t h\frac{\partial u_i}{\partial x_j}\right)+\frac{\tau_i}{\rho}$$

$$\tau_i=\tau_{Si}+\tau_{Wi}-\tau_{bi}$$

$u \rightarrow$ Depth-averaged current velocity

$h \rightarrow$ Total water depth

$\zeta \rightarrow$ Still water depth

$\eta \rightarrow$ Water surface elevation

$g \rightarrow$ Gravity

$p_a \rightarrow$ Atmospheric Pressure

$S \rightarrow$ Precipitation/Evaporation

$f_c \rightarrow$ Coriolis

$\nu_t \rightarrow$ Turbulent eddy viscosity

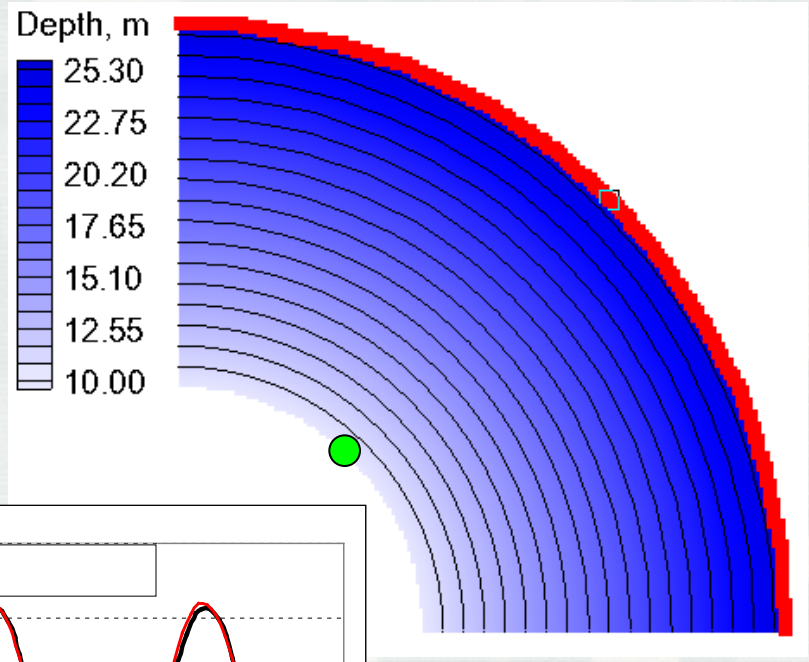
$\tau_b \rightarrow$ Bottom stress (including waves)

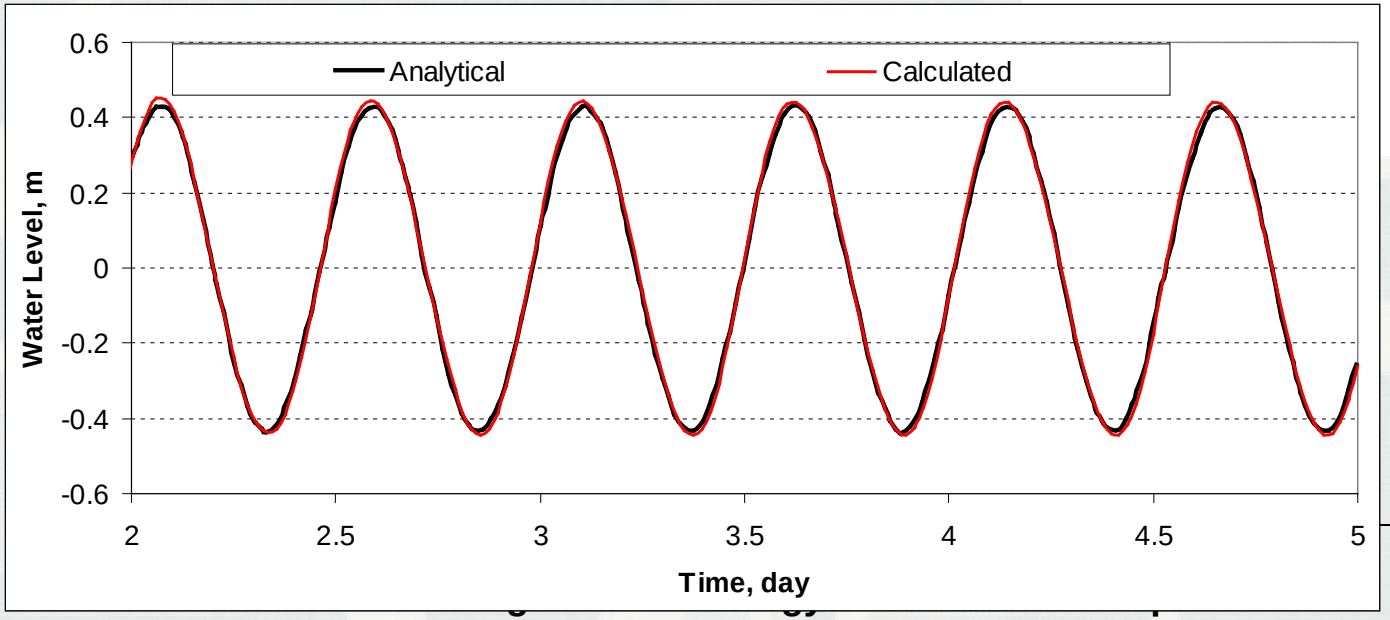
$\tau_S \rightarrow$ Wave stress (forcing)

$\tau_w \rightarrow$ Wind stress

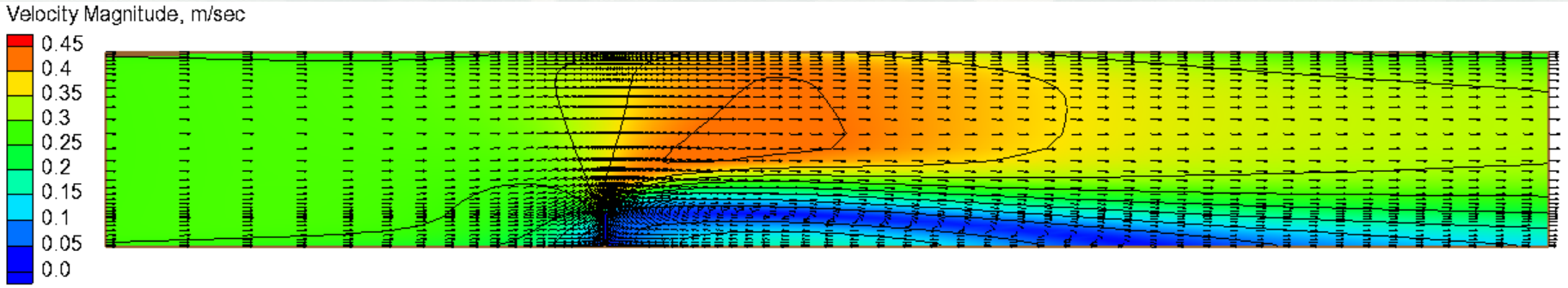
Tidal propagation

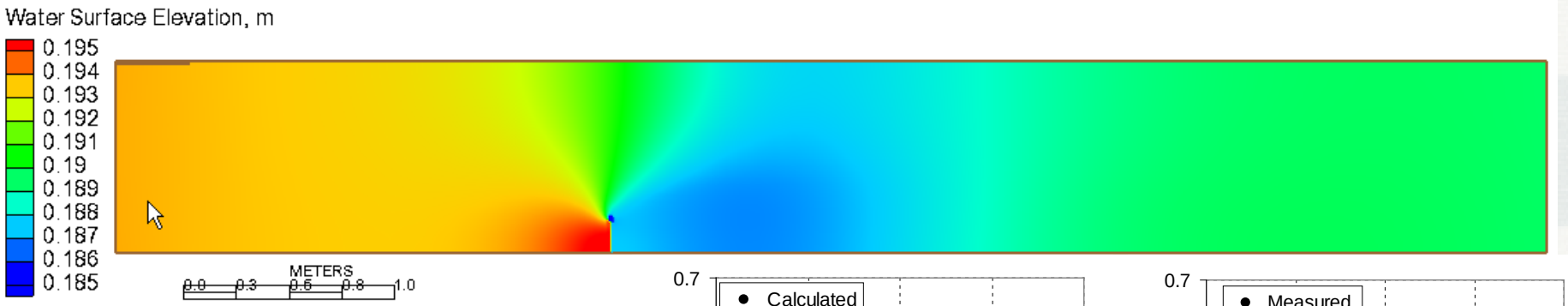
- M2 Tide
- No Bottom friction
- No viscosity
- Time step: 10 min

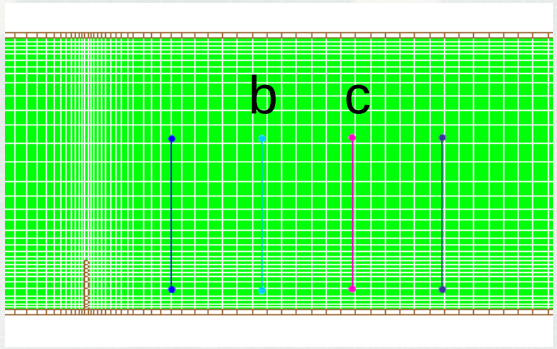


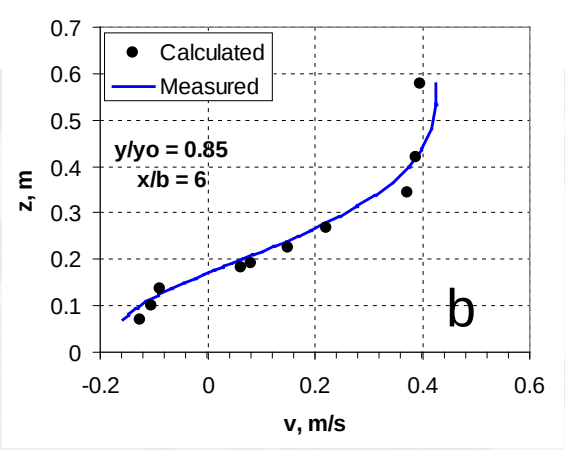


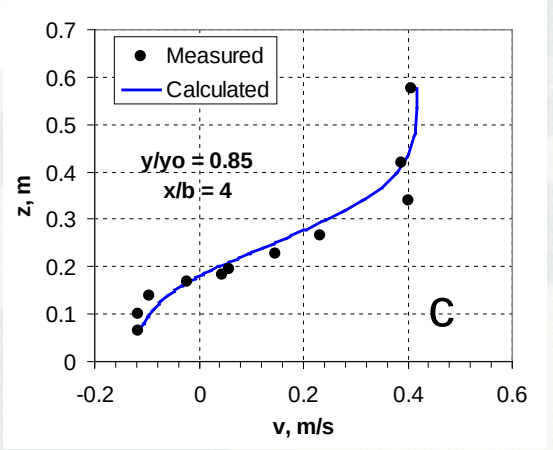
Spur dike case



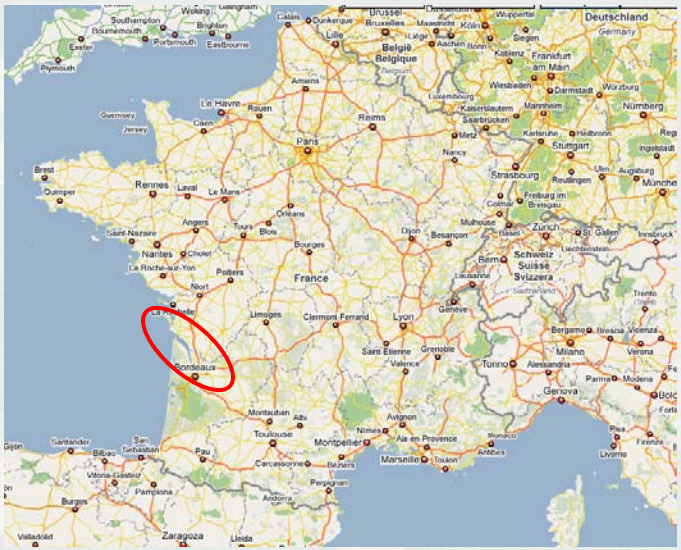


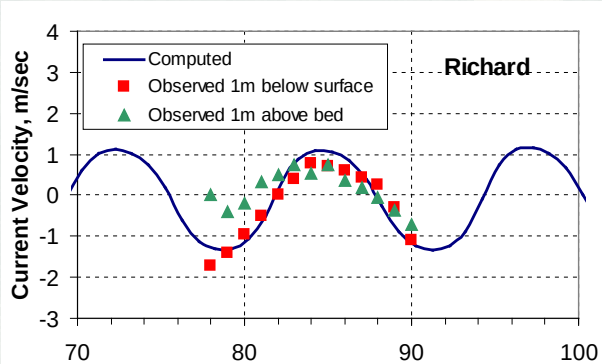


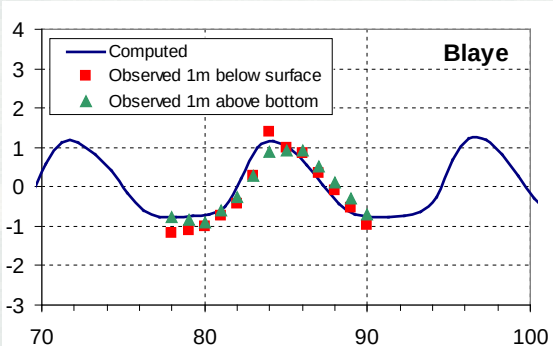


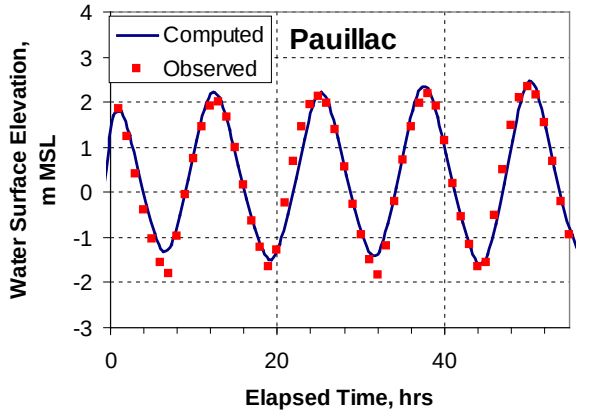


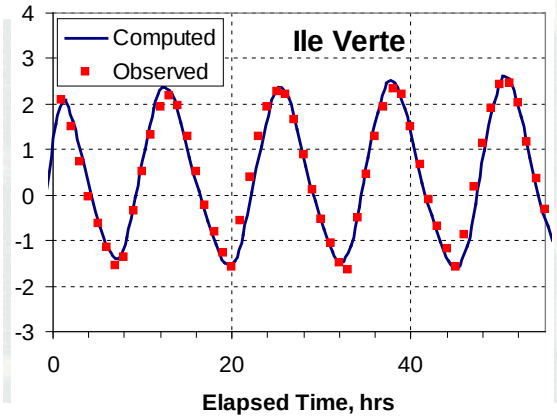
Gironde Estuary, FR

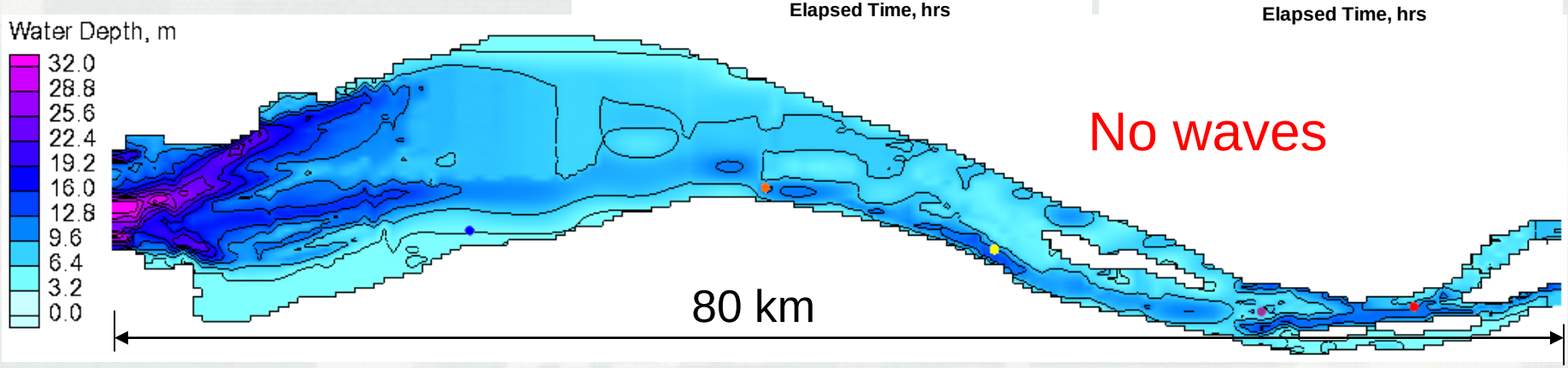










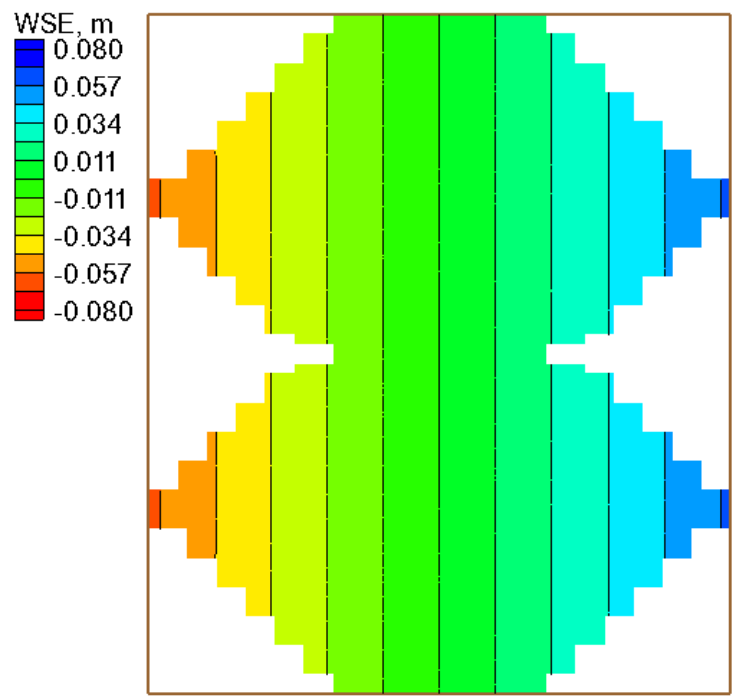


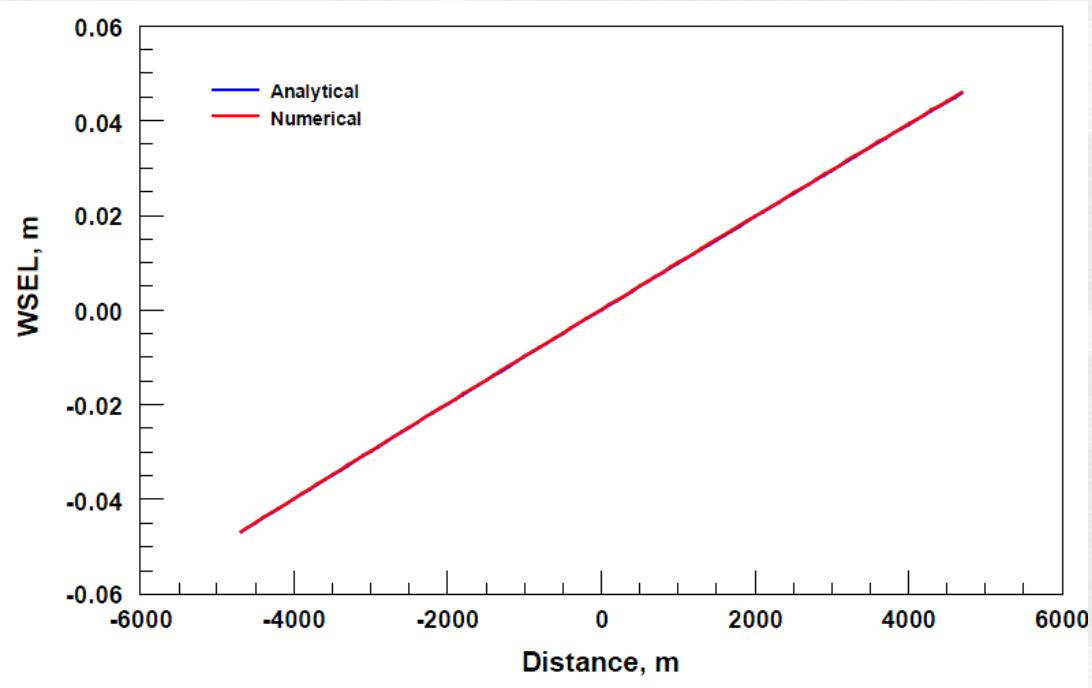
No waves

Wind Setup

(No bottom friction)

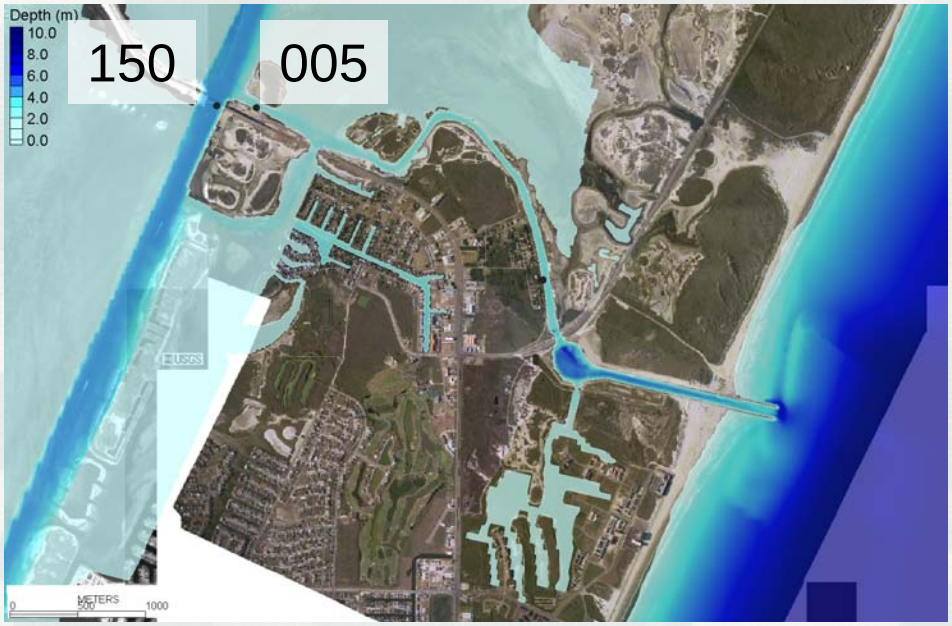
10 m/s Wind

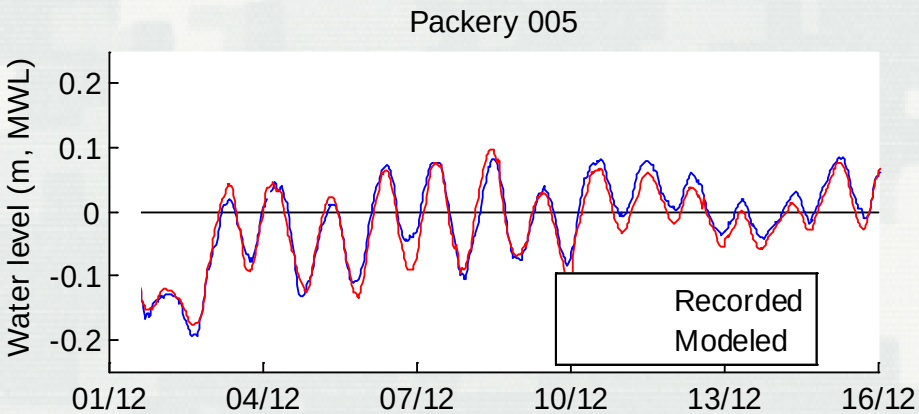


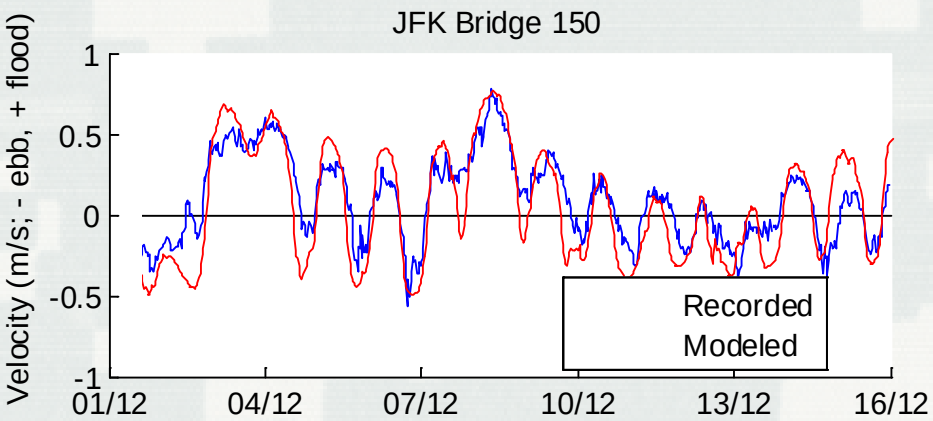


Packery Channel, TX

(No Waves)

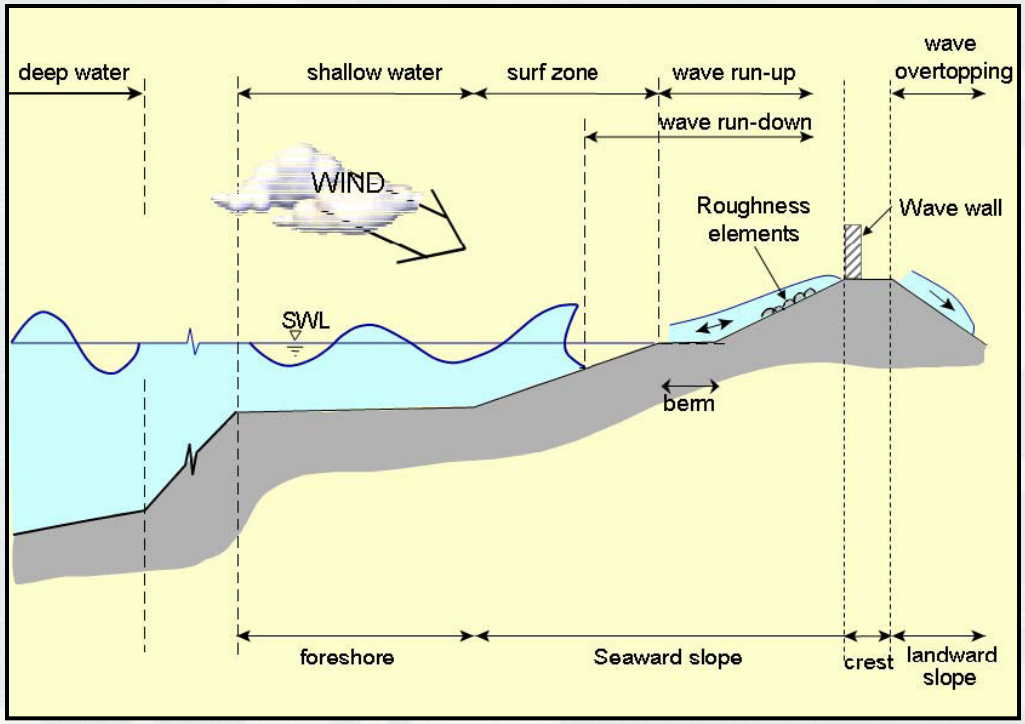






CMS-Wave: Key Features

- Shoaling, refraction, diffraction, reflection
- Bottom friction
- White capping
- Wave breaking (4 options)
- Wind generation
- Current-wave, and wave-wave interactions
- Transmission, runup and overtopping
- Muddy bottom
- Automatic grid rotation
- Non-uniform Cartesian grid with nesting capability
- “Fast Mode”



Spectral Wave Transformation

Wave-Action Balance Equation with Diffraction

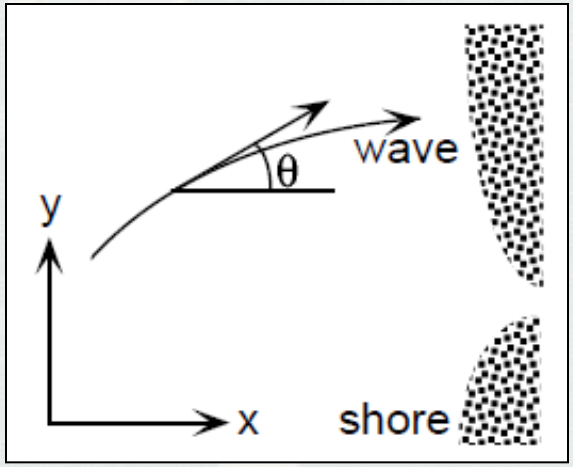
Diffraction intensity factor

$$\frac{\partial(c_x A)}{\partial x}+\frac{\partial(c_y A)}{\partial y}+\frac{\partial(c_{g\theta} A)}{\partial \theta}=\frac{\kappa}{2\sigma}\{(cc_g\cos^2\theta A_y)_y-\frac{1}{2}cc_g\cos^2\theta A_{yy}\}+S_{in}+S_{dp}$$

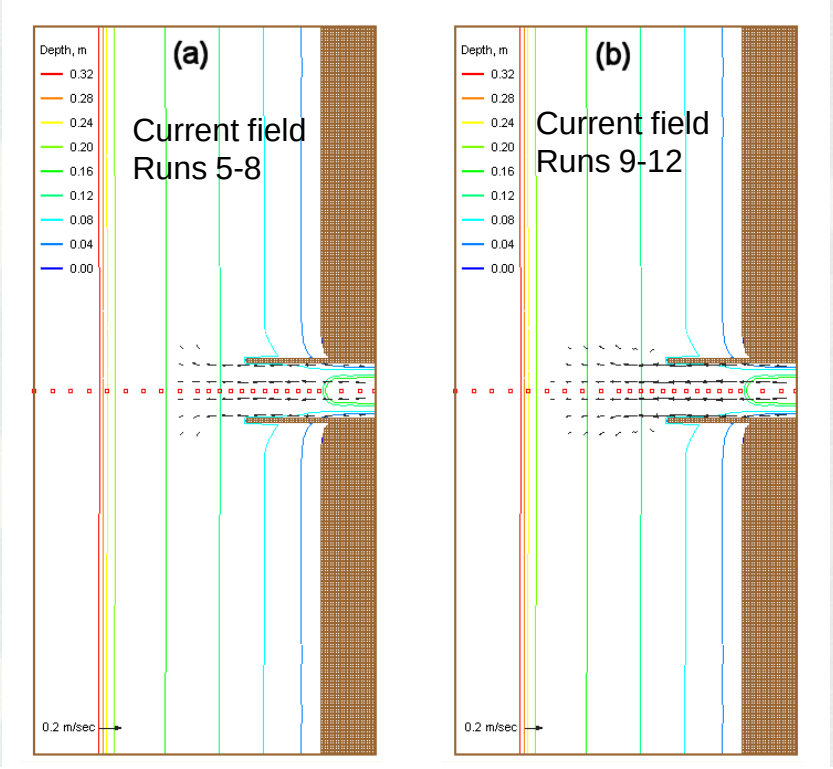
where $A=E/\sigma$, wave-action spectrum

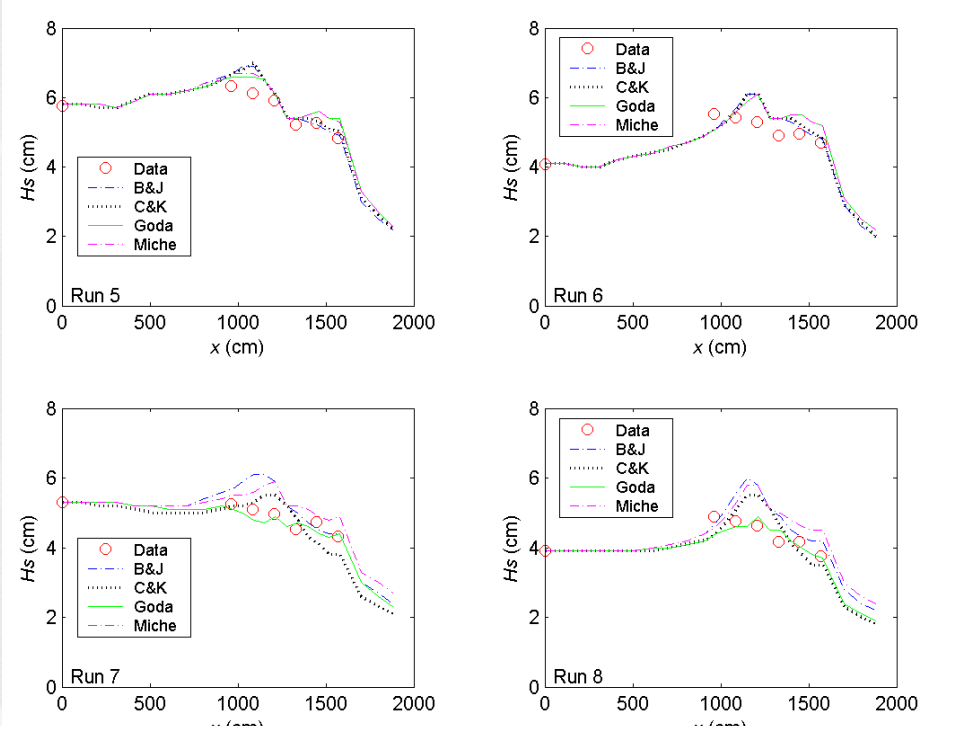
and $E=E(\sigma,\theta)$, wave directional spectrum

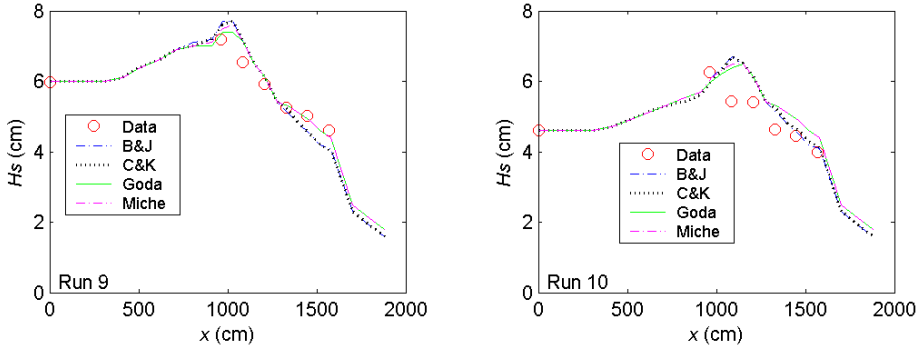
Note: *x* is normal to the offshore boundary; *y* is parallel to the offshore boundary



Wave Breaking

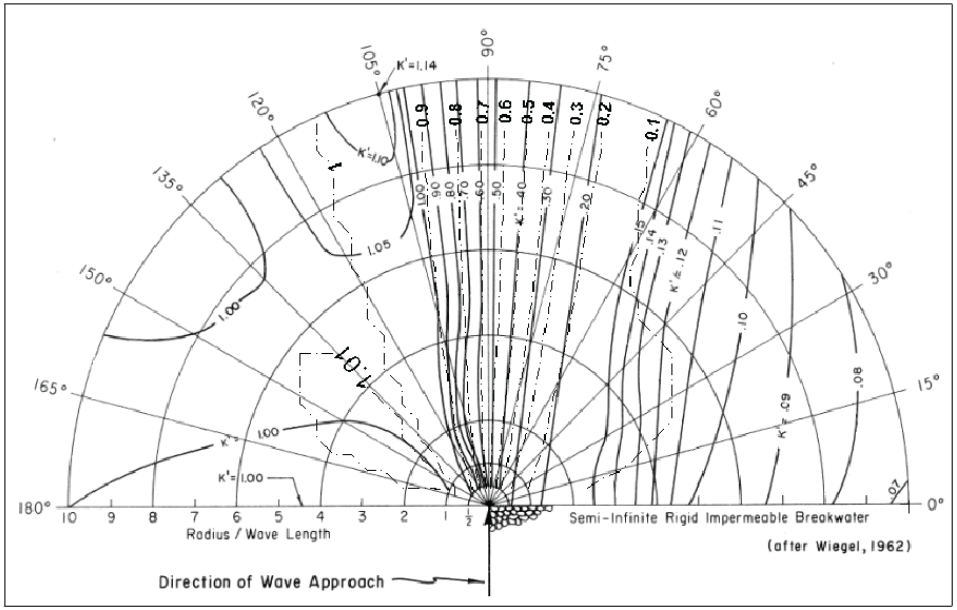


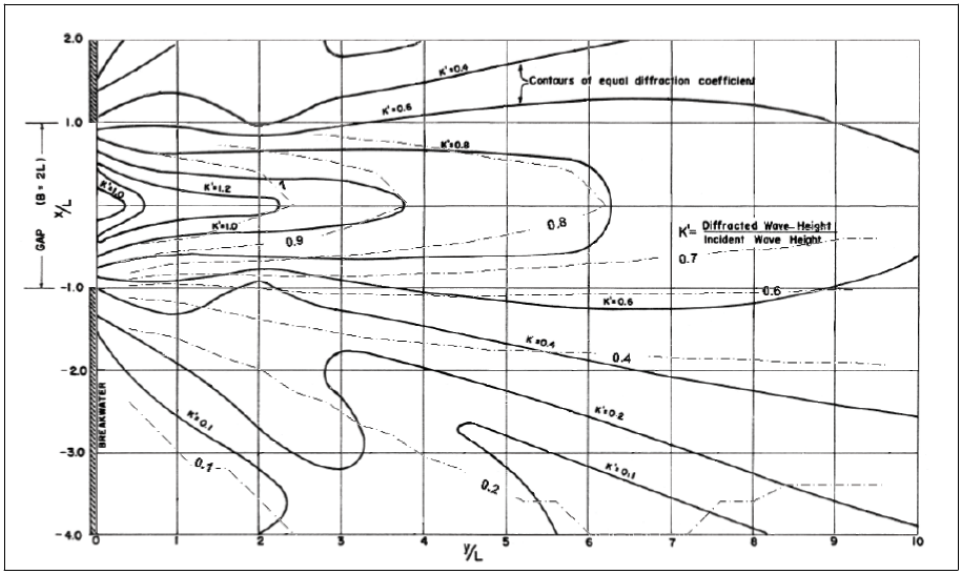




Wave Diffraction

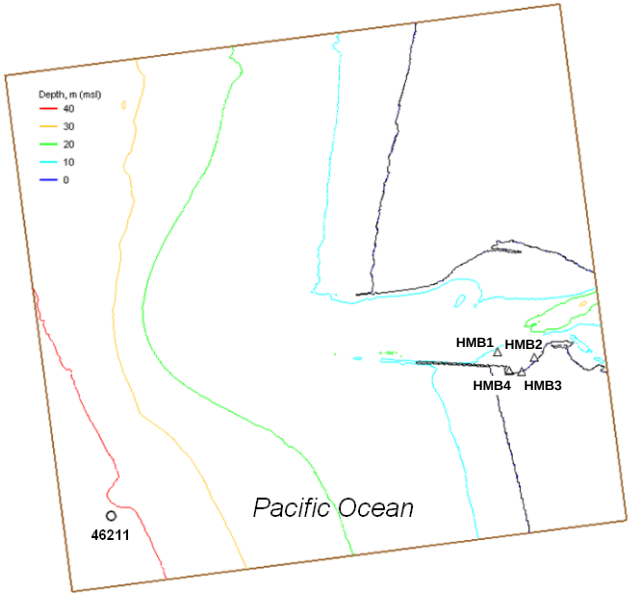
Comparison of computed and measured wave diffraction coefficients

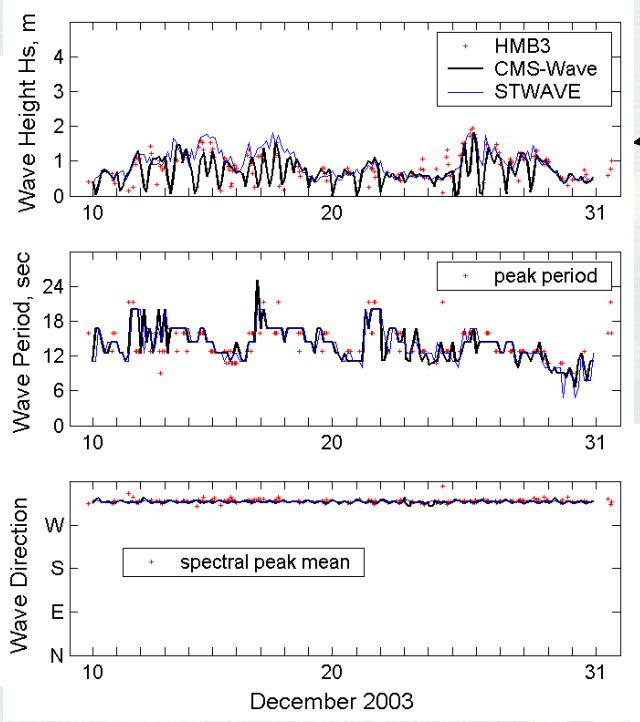




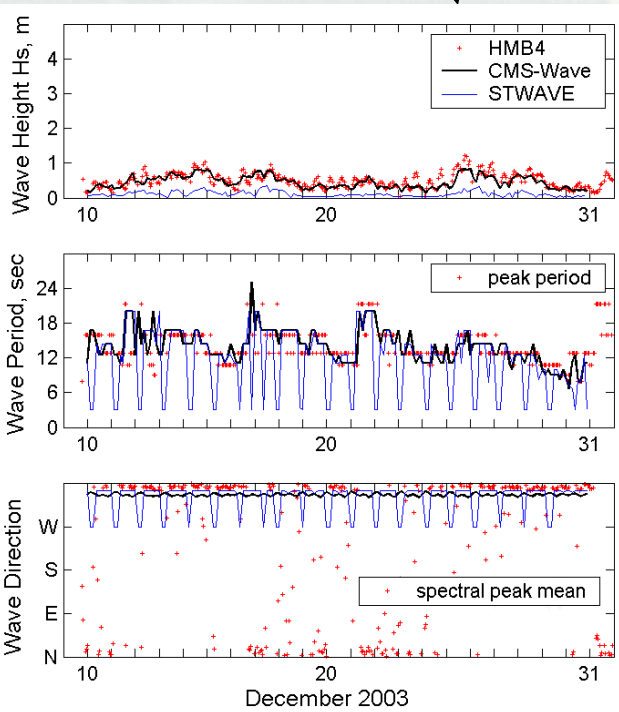
Validation: Half-Moon Bay, WA
CMS-Wave and STWAVE Simulation

Numerical model domain



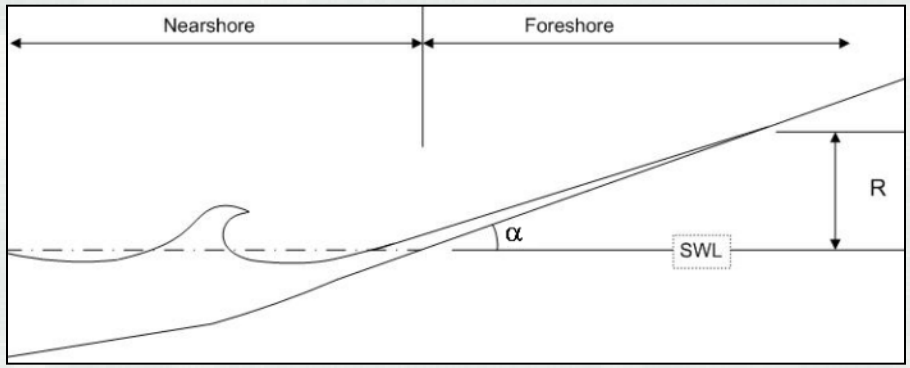


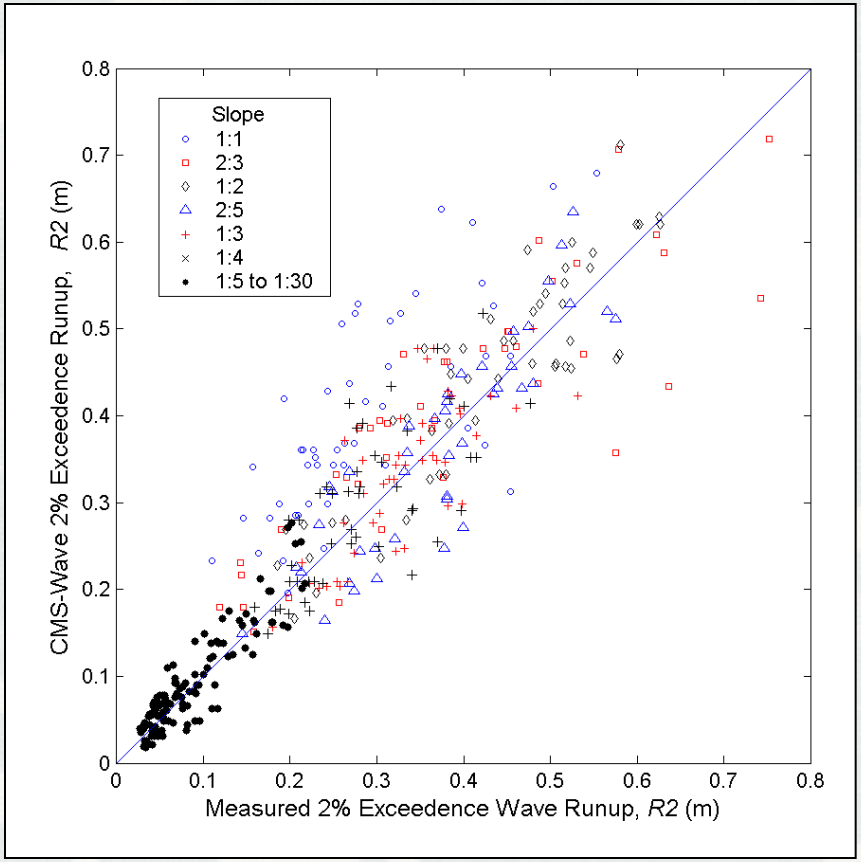
HMB3 and HMB4 are located in the lee of South Jetty wave diffraction area



Water level data: Regional ADCIRC output
Wave input data: Coastal Data Information Buoy 46211
Wind input data: National Data Buoy Center Buoy 46029
Wave and current station: Half-Moon Bay (HMB1 to 4)
Wave Simulation: 20-day (10-30 December 2003)
Time-step: 3-hr interval

Wave Run-up



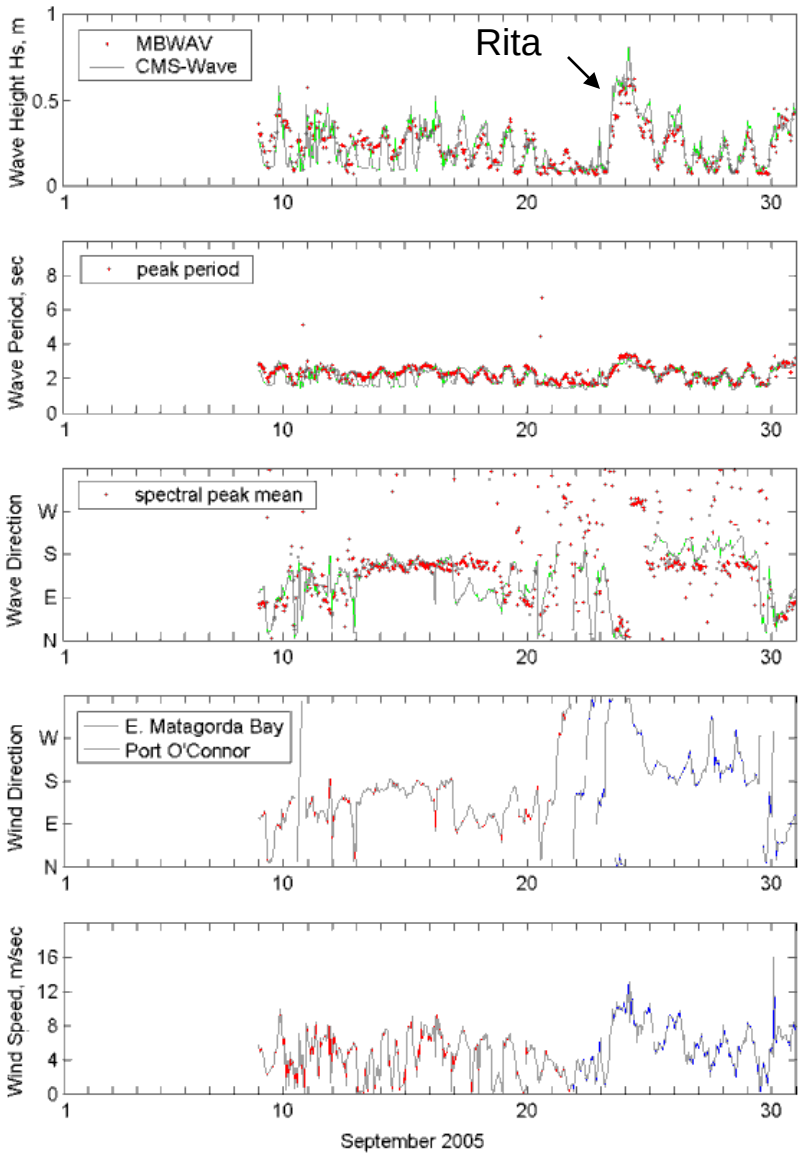


Wave run-up: rush of waves up a slope or structure

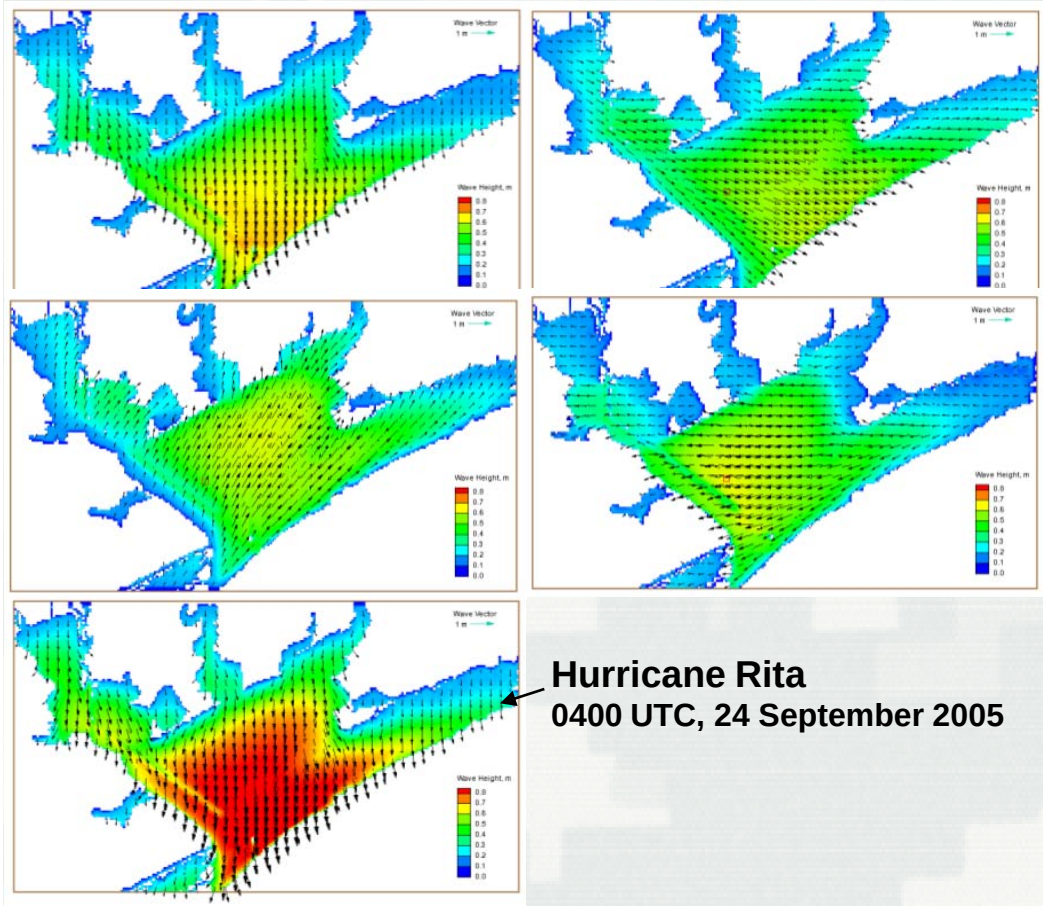
Two-percent run-up, *R2* : the vertical up-rush level exceeded by 2-percent of the larger run-up height

Ahrens & Titus (1981), Mase & Iwagaki (1984)
~ 400 laboratory experiments

Wave Generation

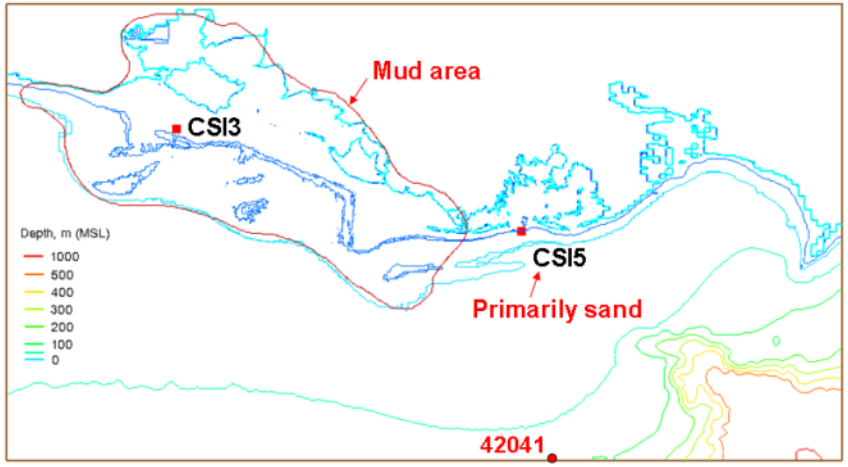


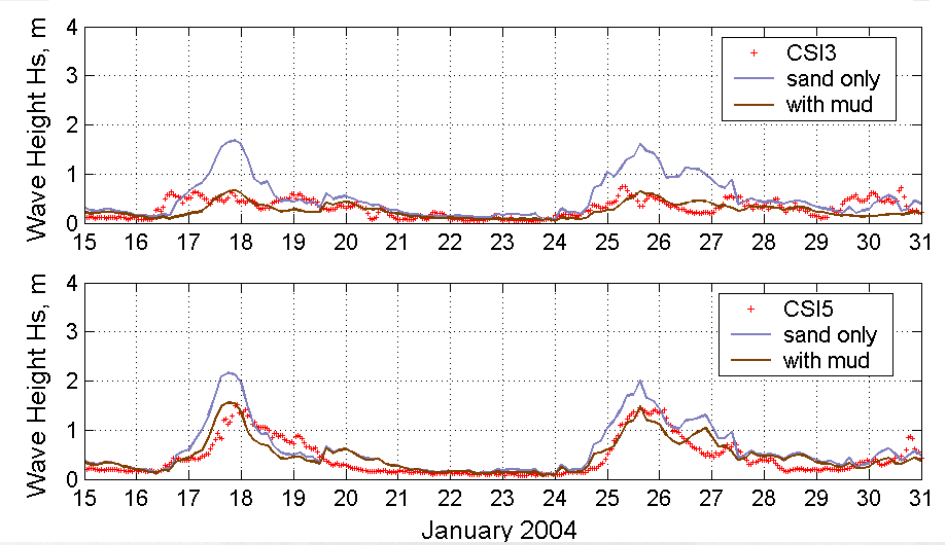
Matagorda Bay, TX

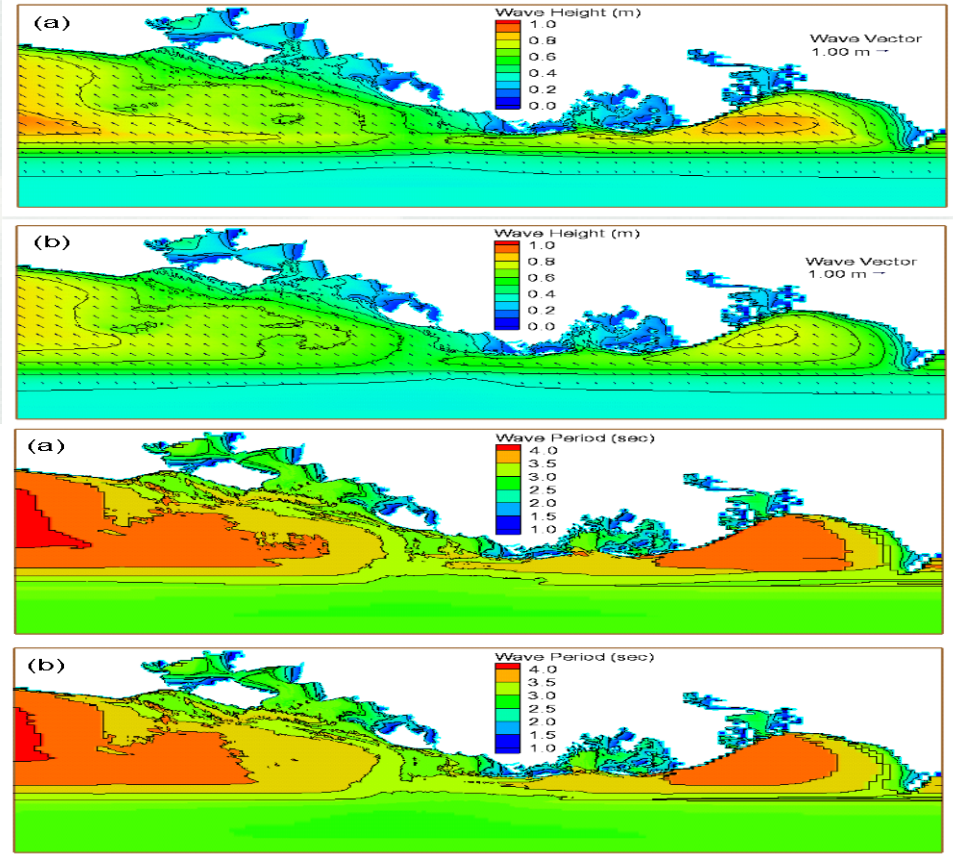


Hurricane Rita
0400 UTC, 24 September 2005

Wave Dissipation over Muddy Coast





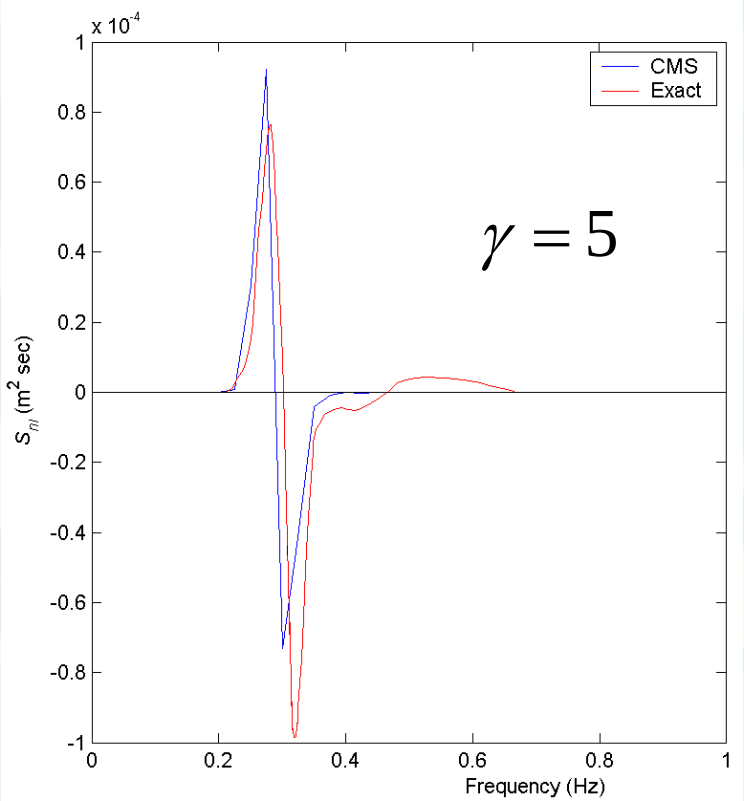


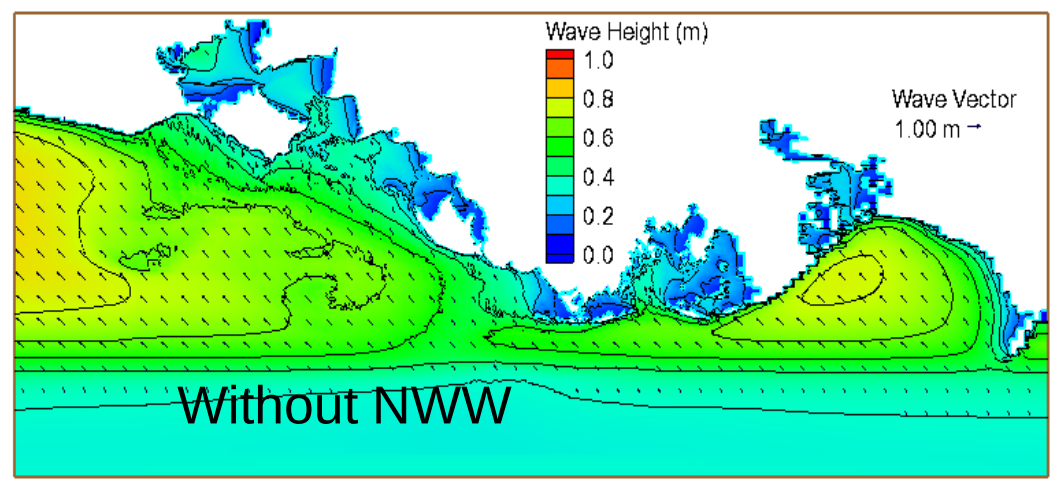
$$S_{mud} = -4\nu_{turb} k^2 E$$

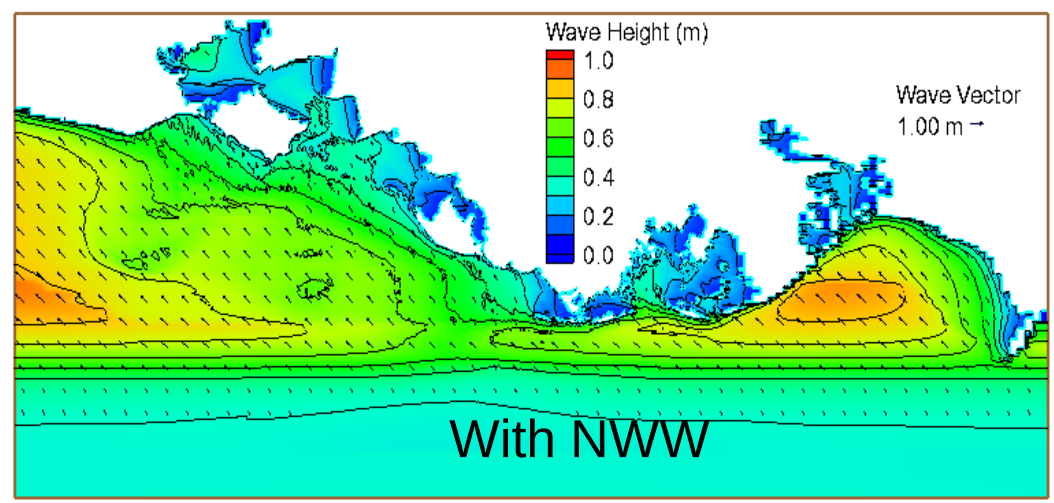
Lamb (1932)

Nonlinear Wave-Wave Interaction

- Based on Jenkins and Phillips (2001)

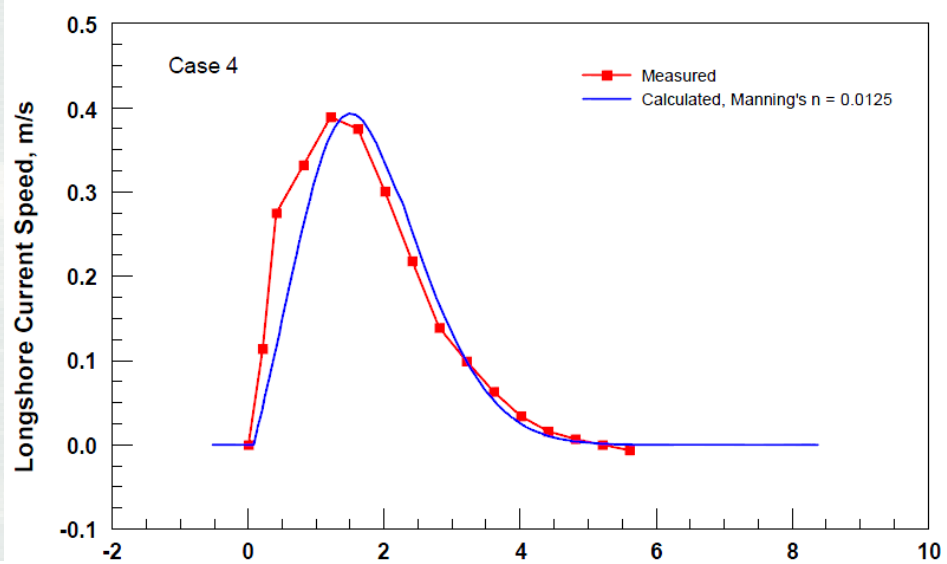


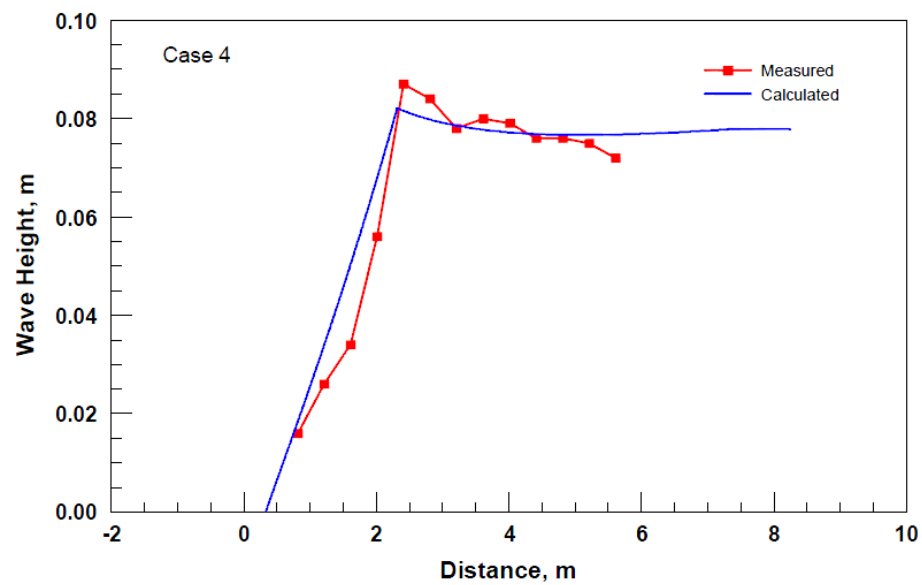


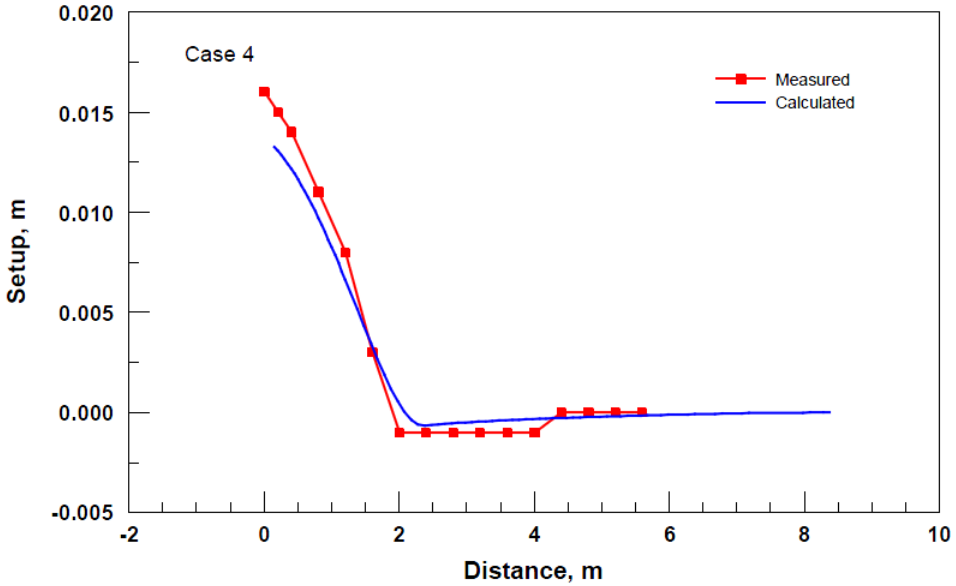


Wave-current Interaction

- Visser Case 04
- Height = 0.078 m
- Period = 1.02 sec
- Angle = 15.4 deg

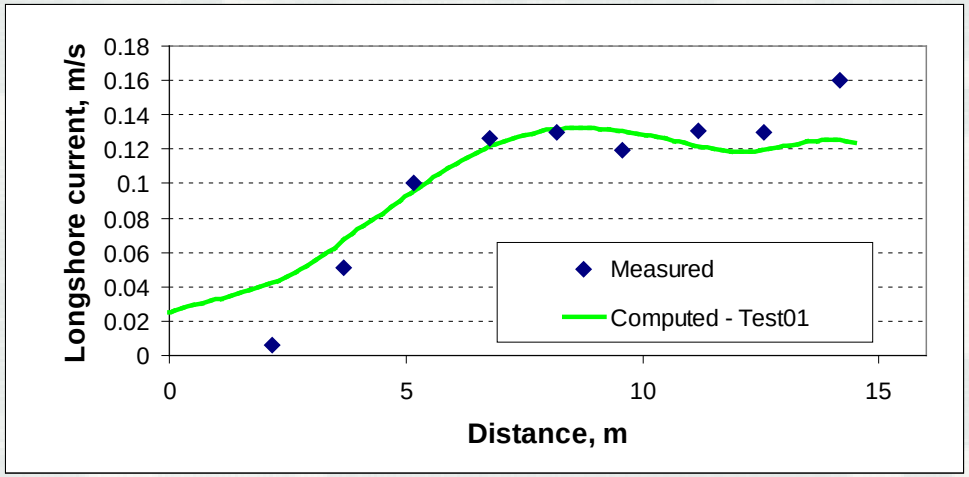


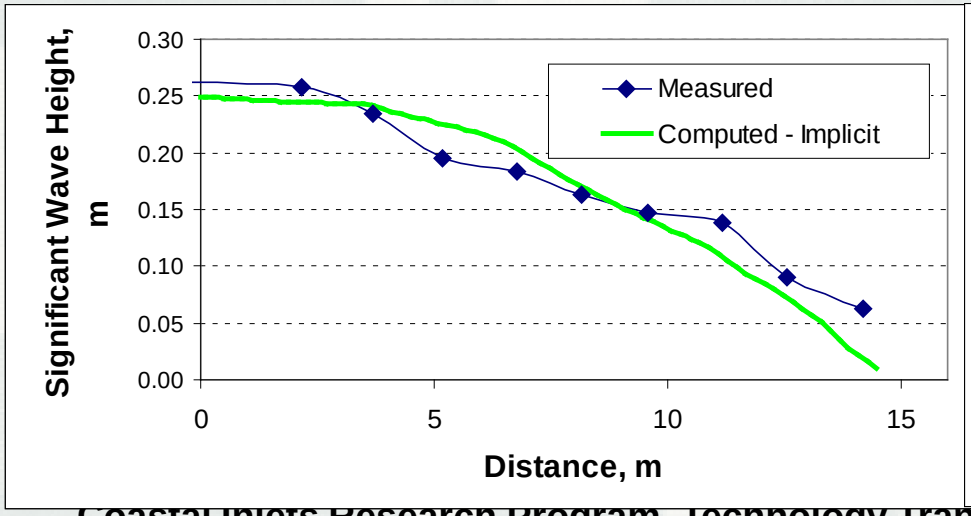


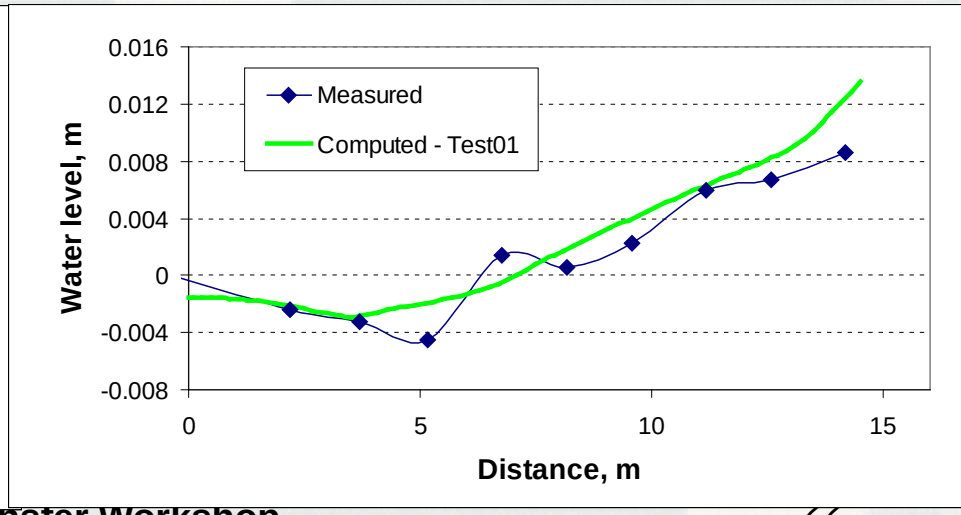


Wave-current Interaction

- LSTF Test 01
- Hs = 0.25 m
- Tp = 1.5 sec
- Angle = 10 deg



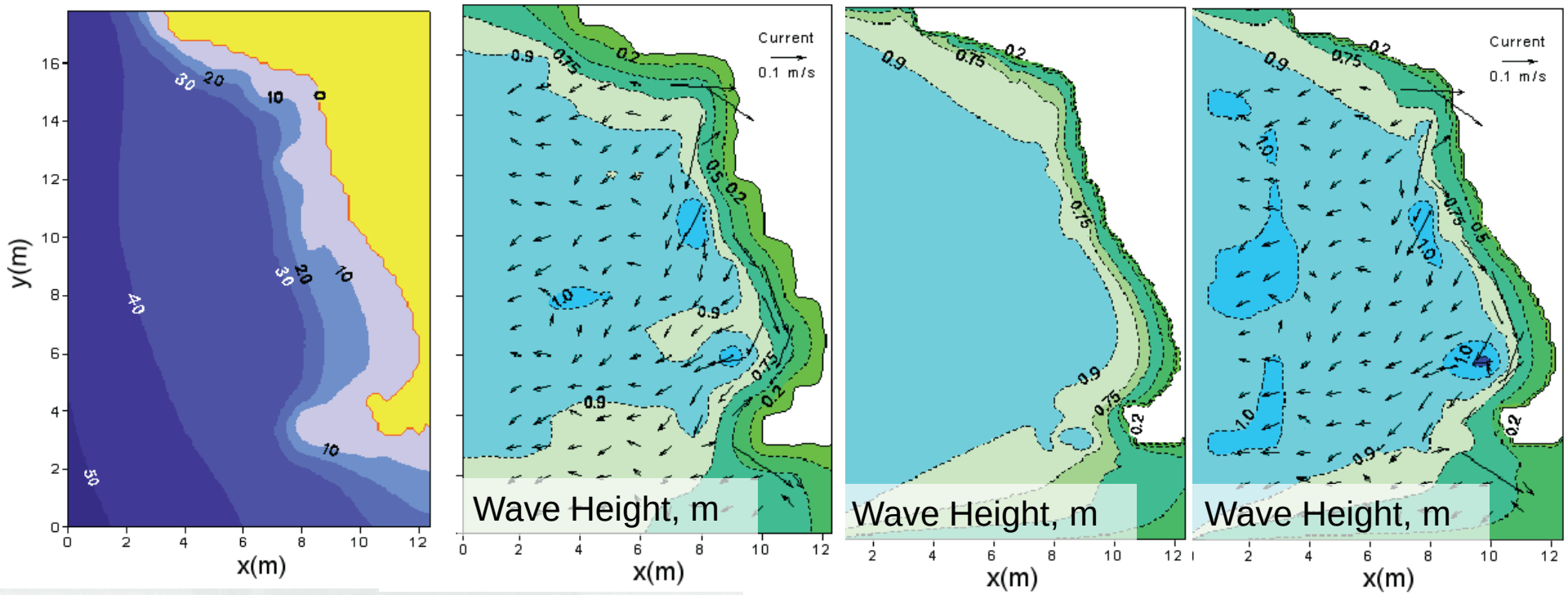




Wave-current Interaction

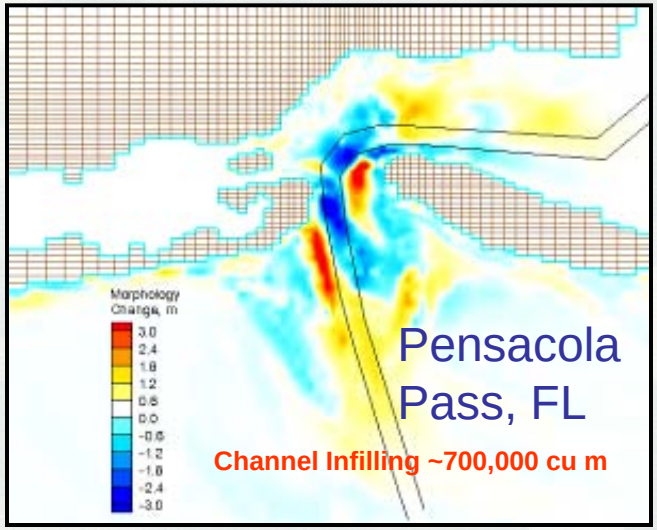
Laboratory Experiment from Japan

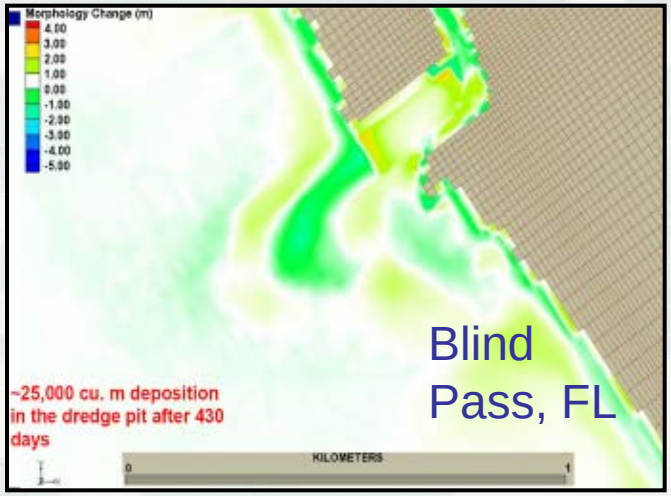
Bathymetry | Measured | No Currents | With Currents



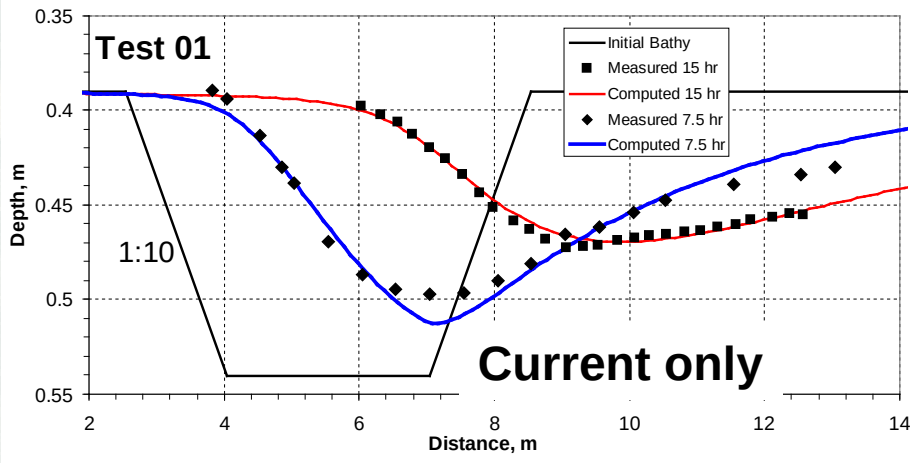
Sediment Transport: Key features

- Sediment transport models
  - Equilibrium Total Load (Exner equation)
  - Eq. Bed Load + AD Suspended Load
  - Non-Eq. (AD Total Load)
- Sediment transport formulas
  - Lund-CIRP
  - Van Rijn
  - Watanabe
- Hard-bottom
- Avalanching
- Bed slope influence on bed load
- Multiple-sized sed. transport (NEW)

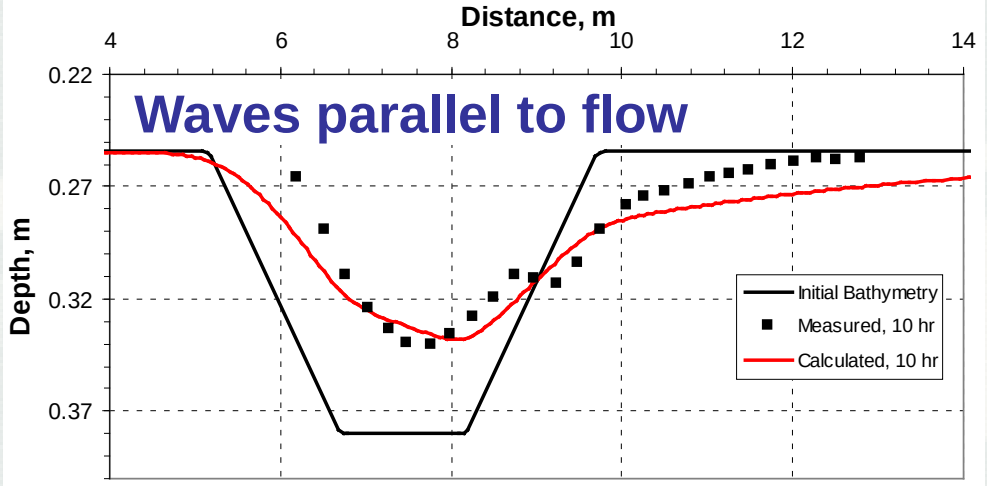




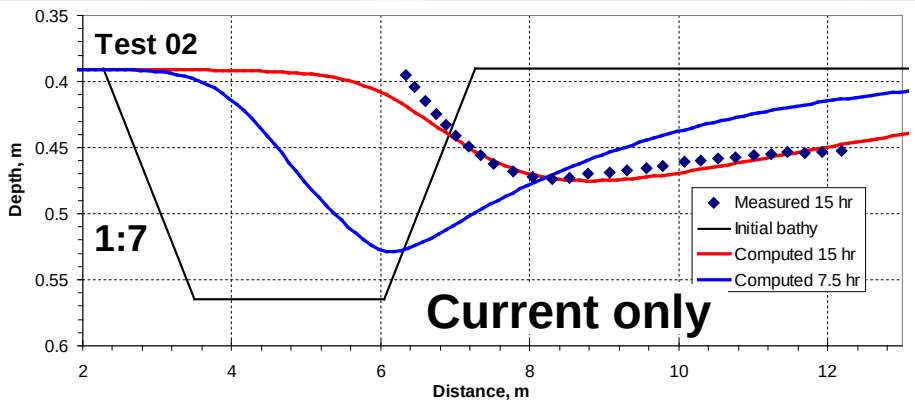
Channel Infilling



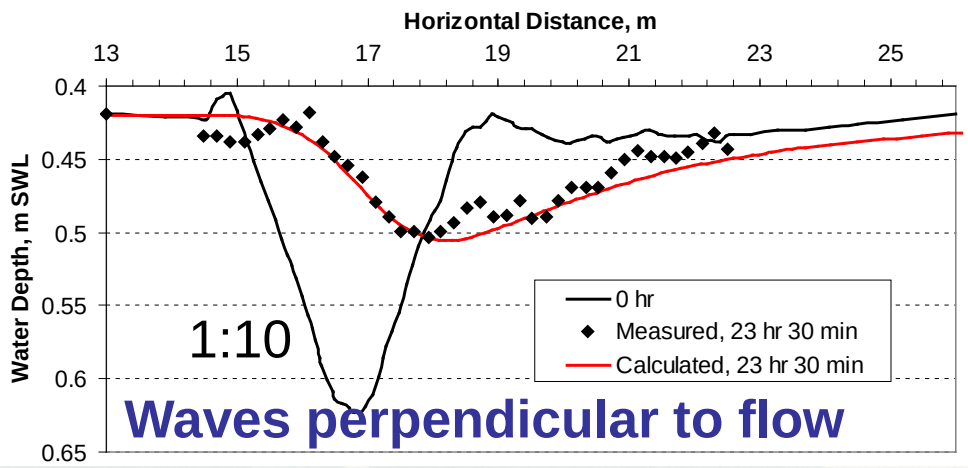
Galappatti and Vreugdenhil (1985)



Van Rijn (1985)



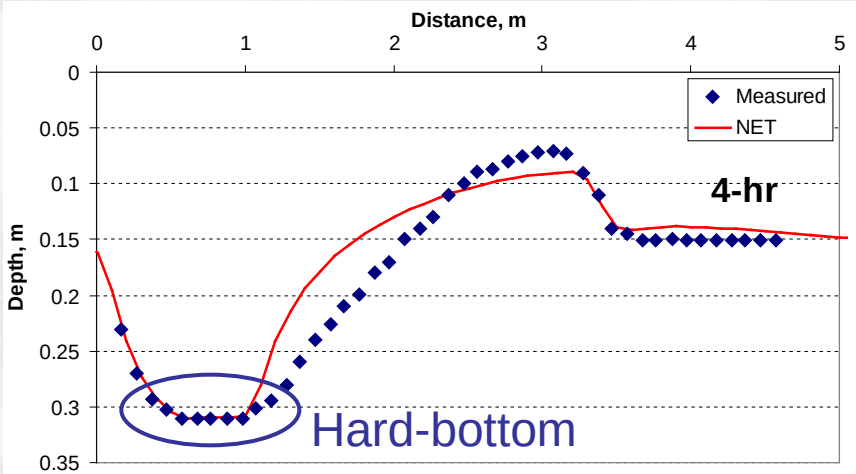
Galappatti and Vreugdenhil (1985)

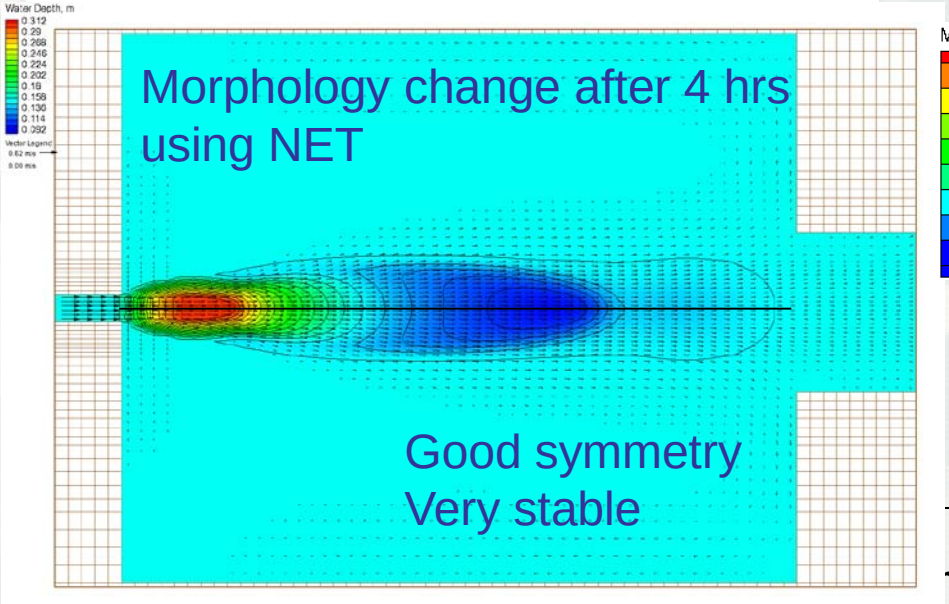


Van Rijn and Havinga (1995)

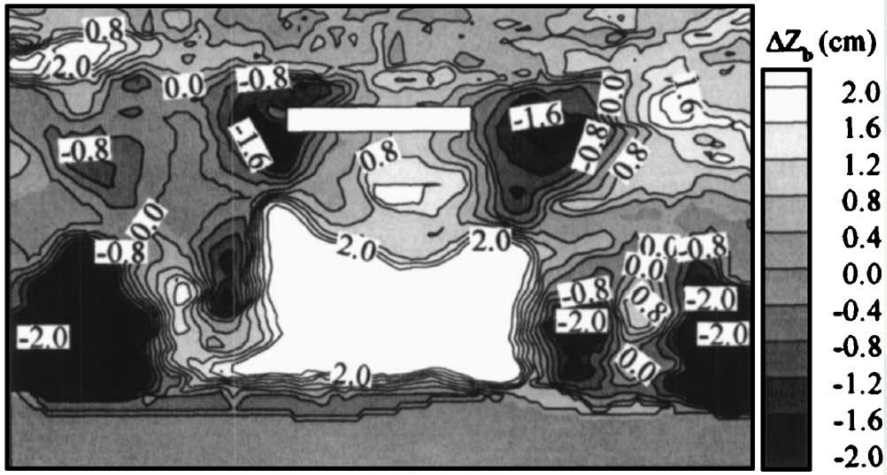
More Validation

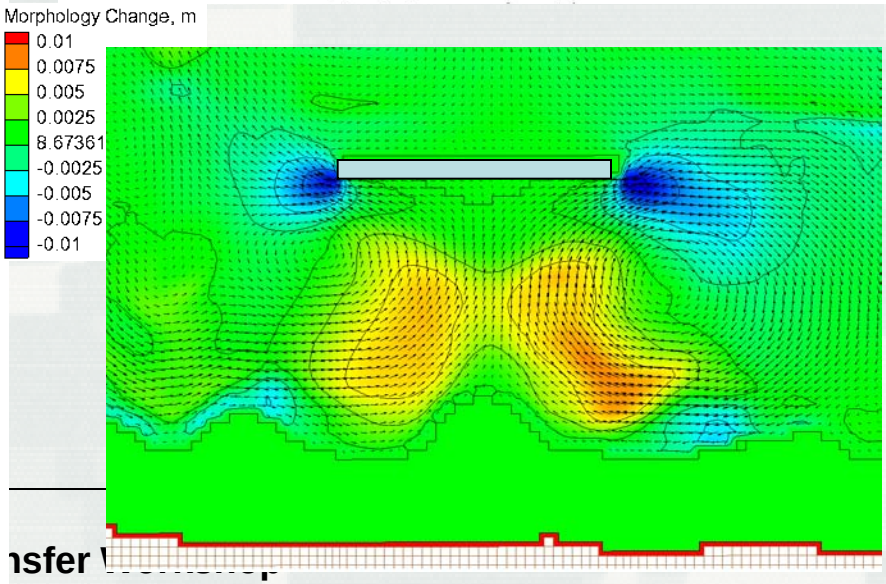
Clear-water Jet (Thuc 1991)





Detached breakwater (Mimura 1983)

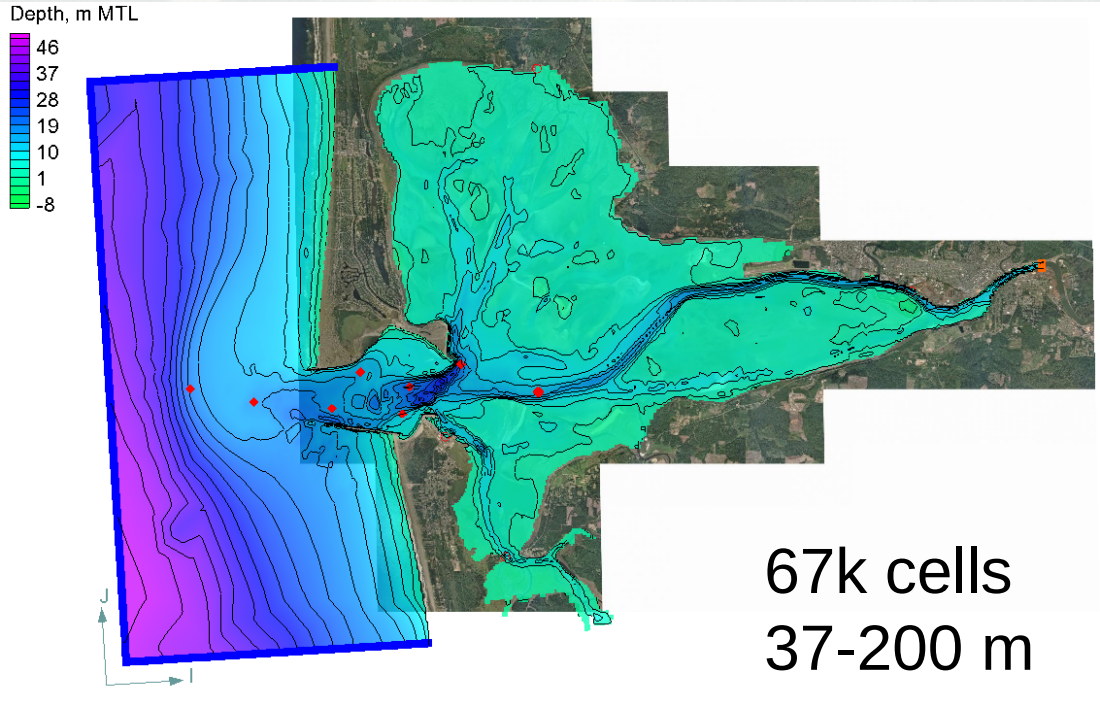




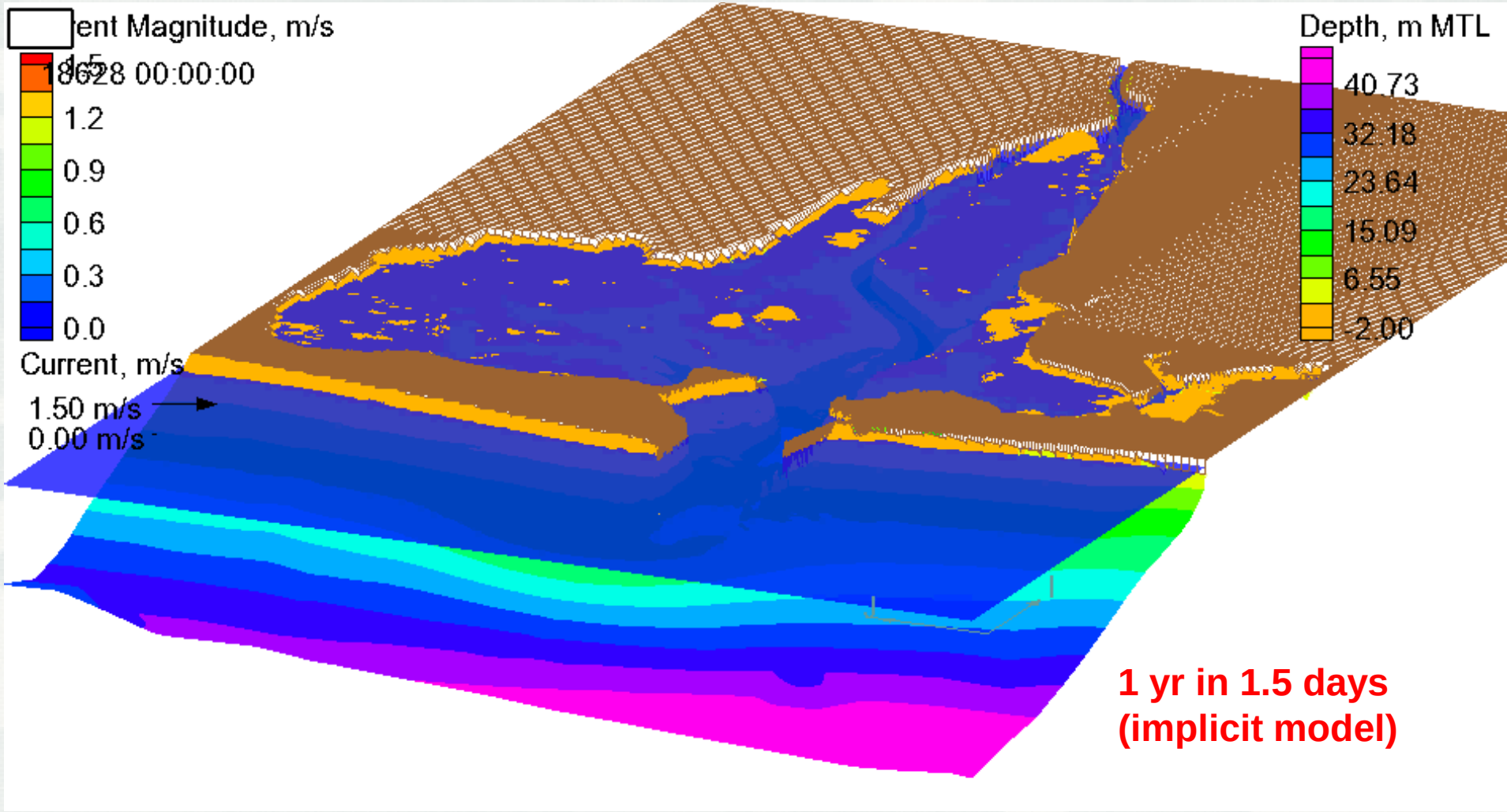
nsfer

Grays Harbor, WA

- Simulation period
  - 27 days Sept-Oct 1999
- Time step (hydro, sed.)
  - 15 min
- Forcing
  - Tide (measured WSE)
  - Wind
  - River
- Non-equilibrium sediment transport
  - Lund-CIRP
- Waves from NOAA buoy
- Steering interval
  - 3 hrs



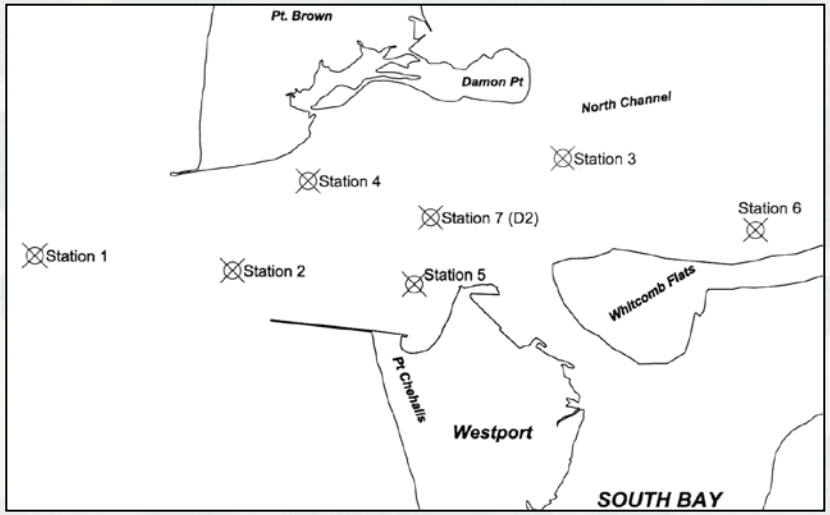
3D SMS Animation - Current Magnitude, Water Surface Elevation, and Water Depth

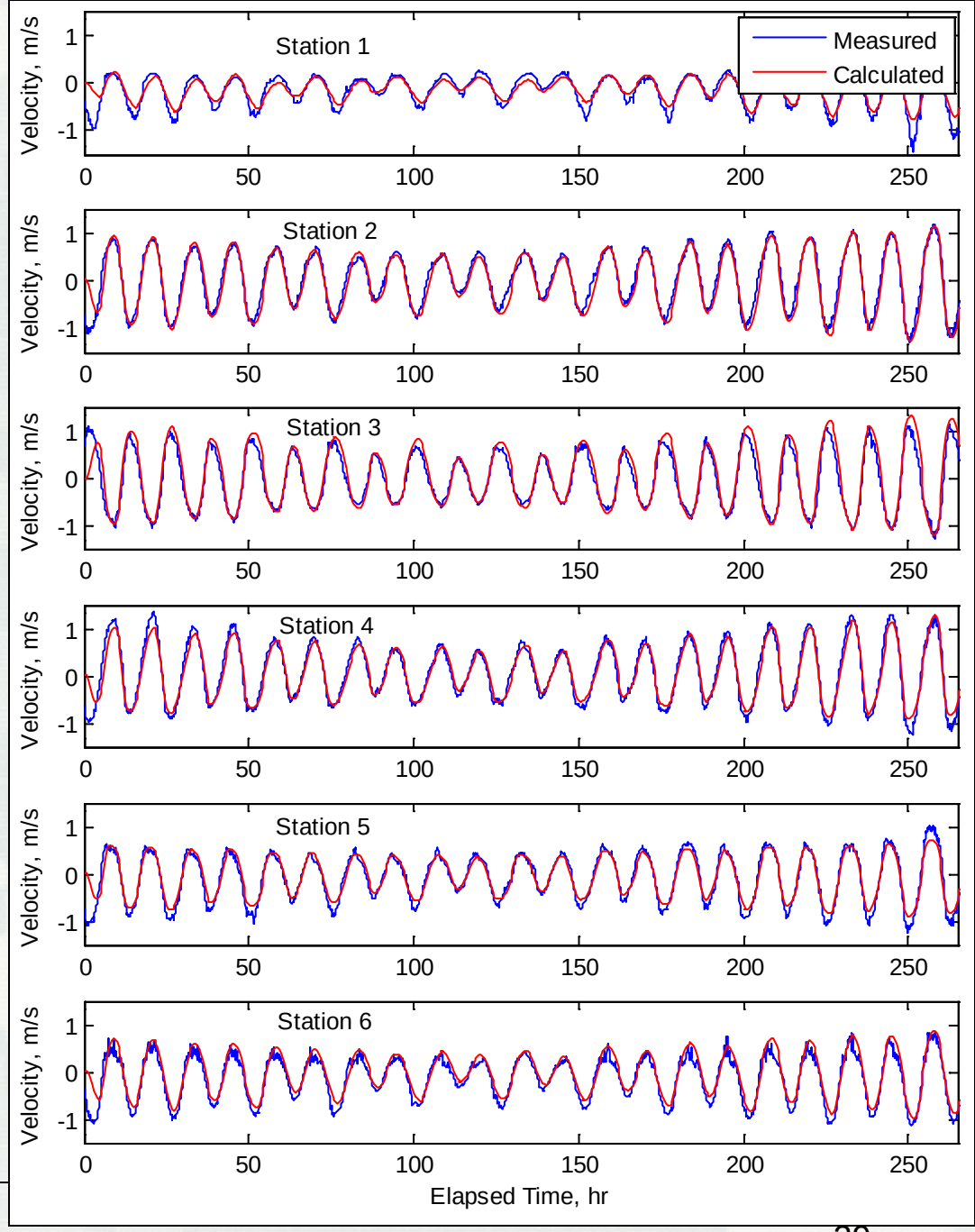


1 yr in 1.5 days (implicit model)

Currents

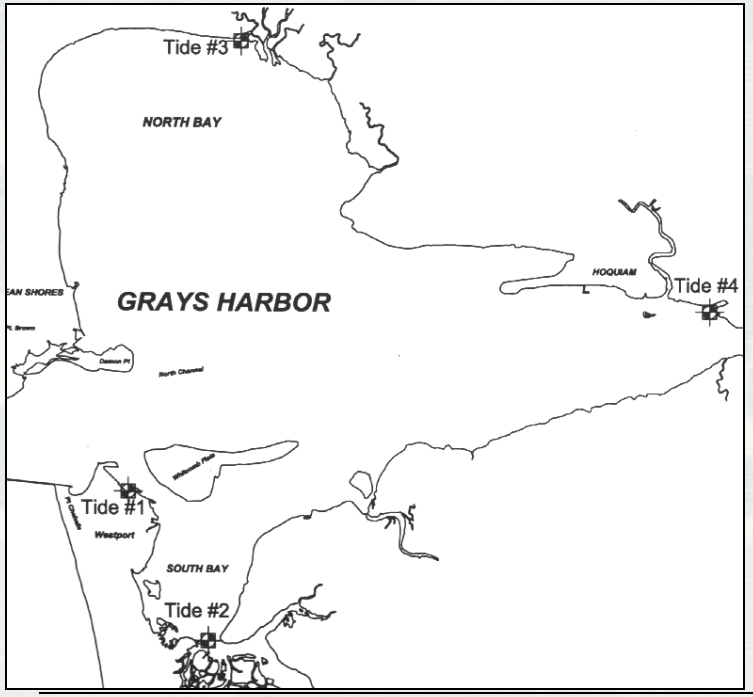
- Depth-averaged current along principle component
- Time from 14 Sep 09

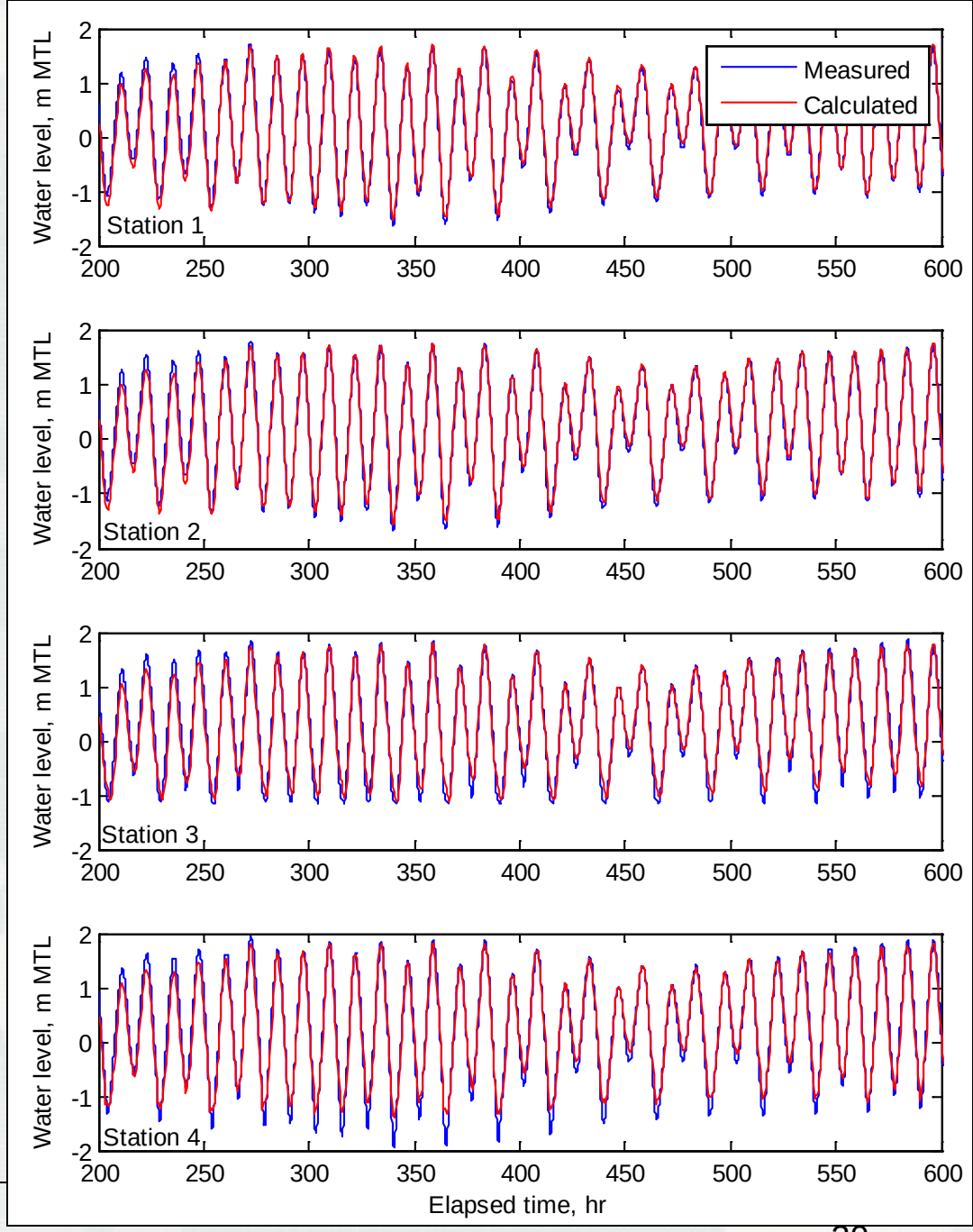




Water Levels

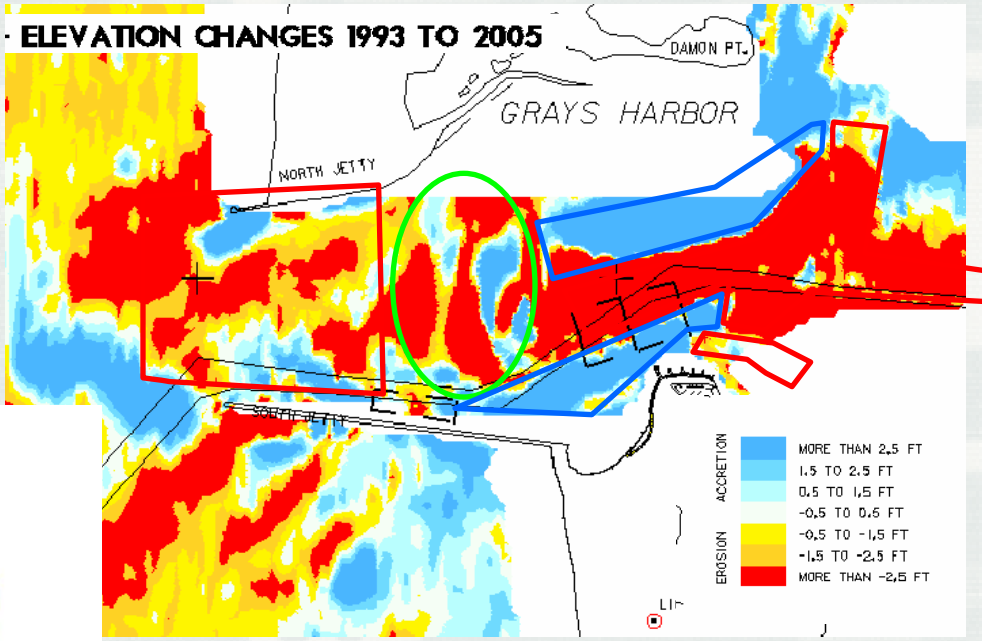
- Ramp up period observed
- Bottom friction likely needs to be adjusted

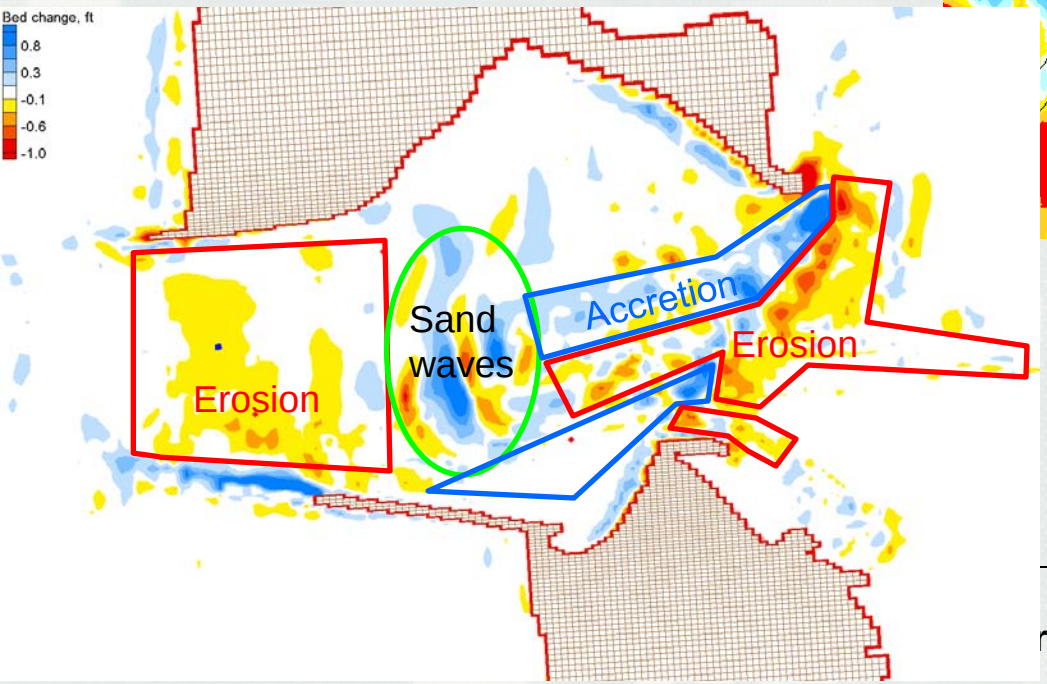




Morphology Change Comparison

- 27-day simulation from 14 Sep 2009
- General patterns captured





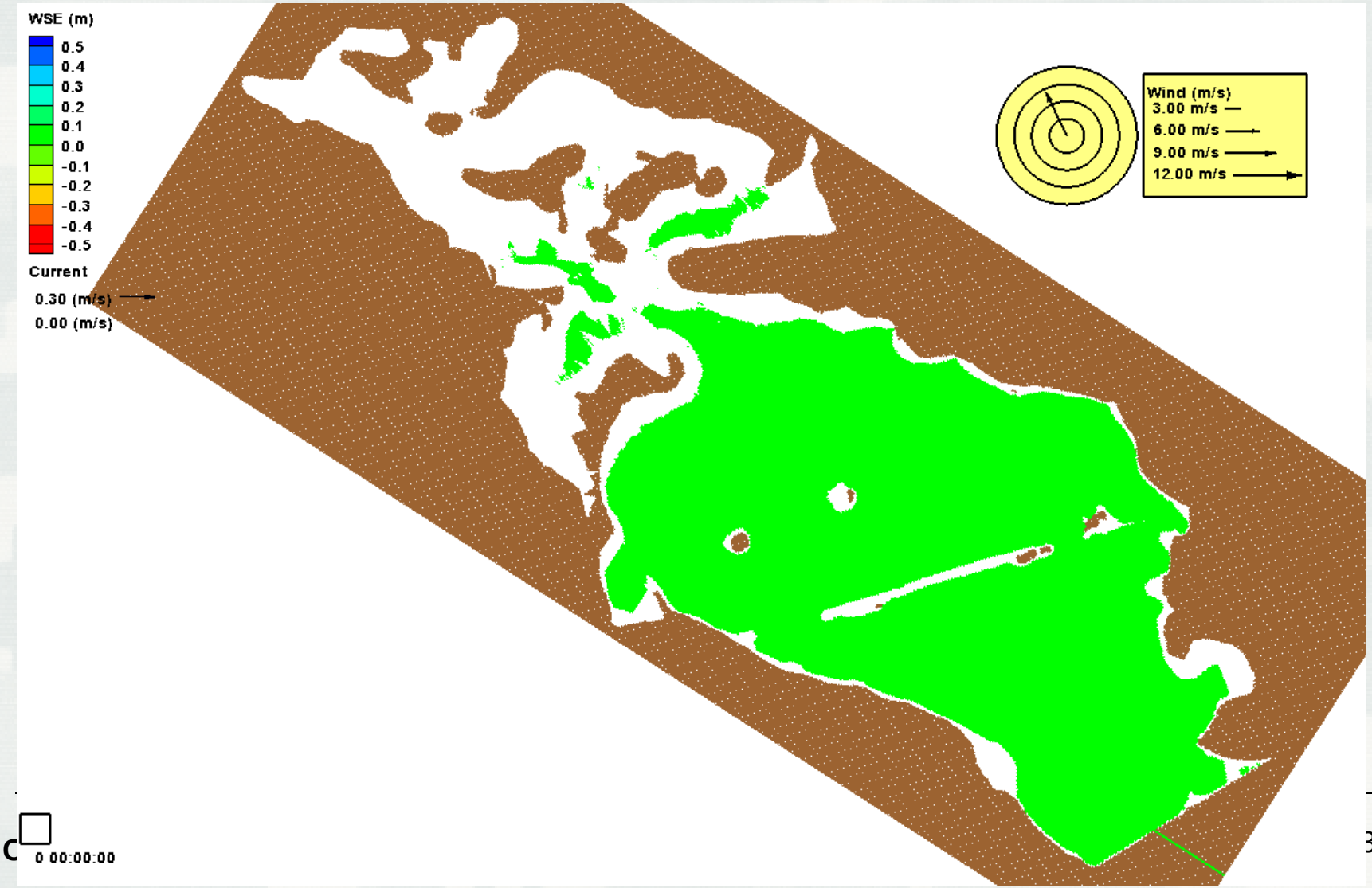
Local differences due to short period trends, sand waves, etc.

Need multi-sized sediment transport

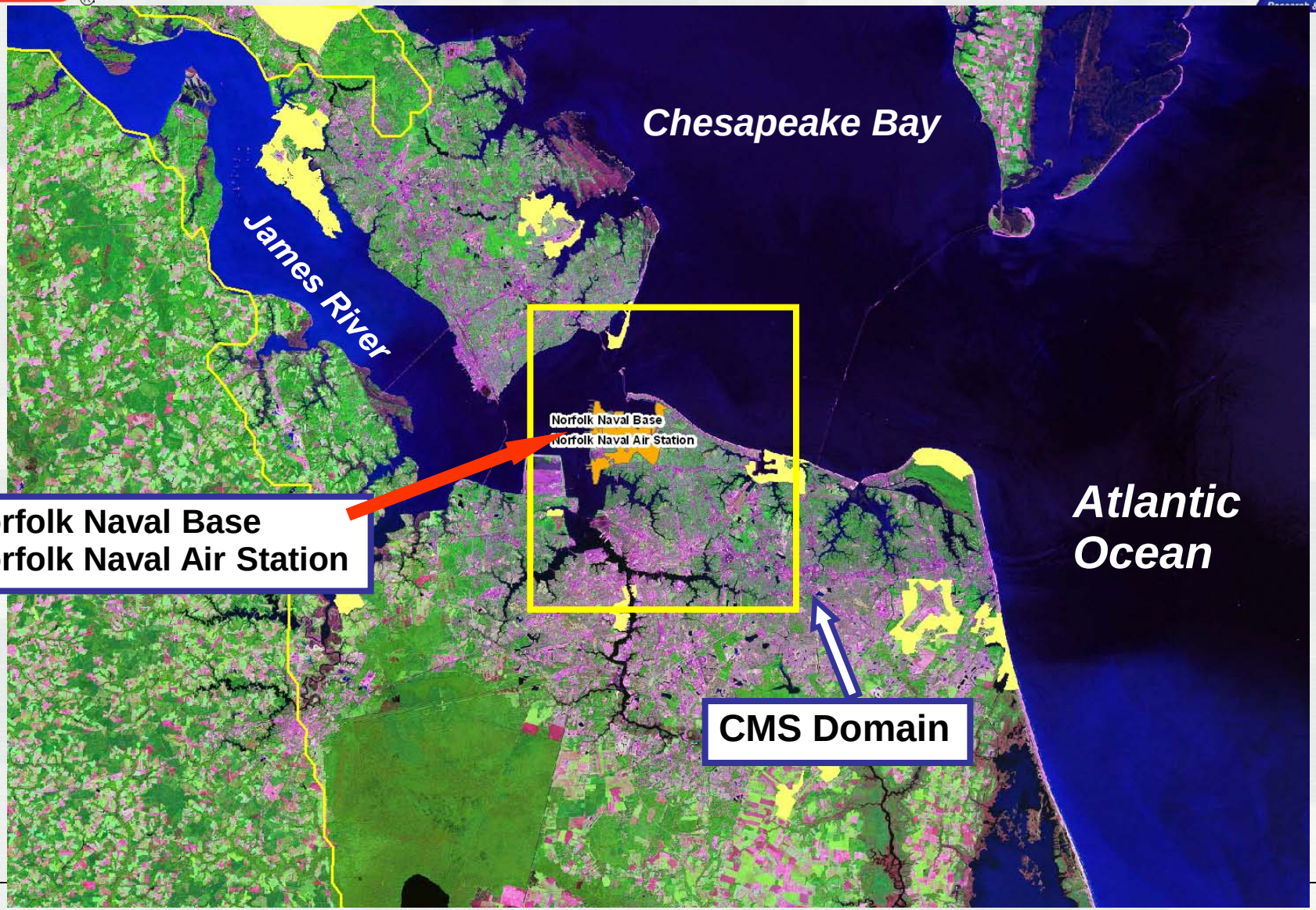
Extreme Wetting/Drying: Bahia Grande, TX

- Remediation, restoration project
- Wind-blown sand is hazardous to power line transformers and human health
- 1:600 slope
- Circulation dominated by wind

Wind Generated Flow in Bahia Grande, TX

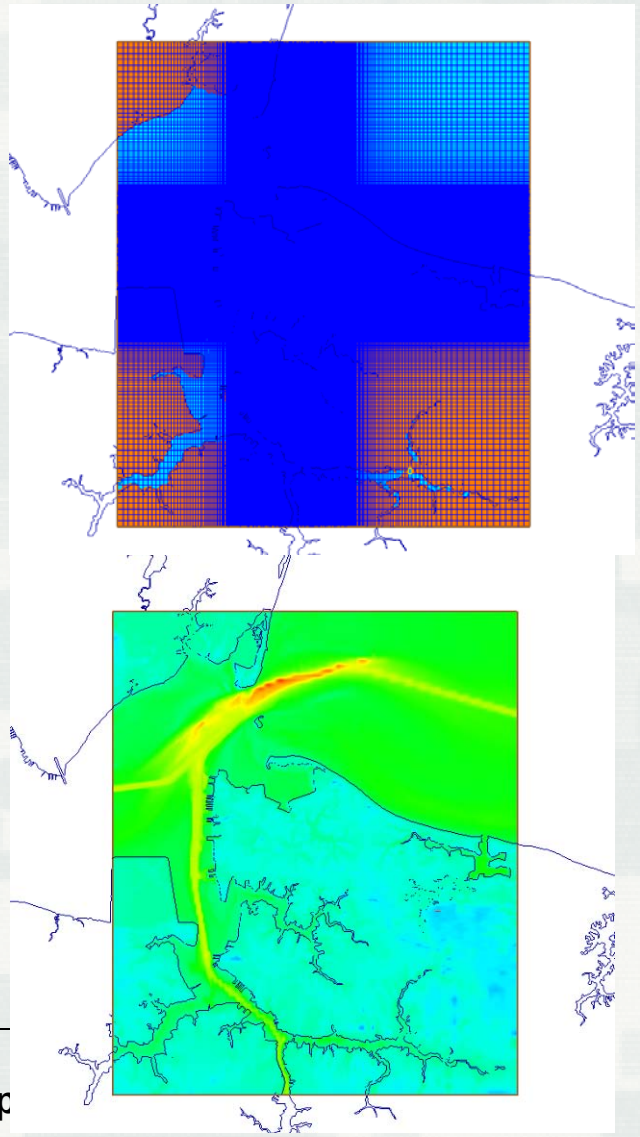


Chesapeake Bay: Storm Surge Flooding



Hurricane Isabel Simulation 17-21 Sep 2003

- Domain Size: 20 x 24 km
- 530k cells (rectilinear grid)
- 10-300 m resolution
- WSE from regional ADCIRC model
- Wind and atmospheric pressure from PBL model

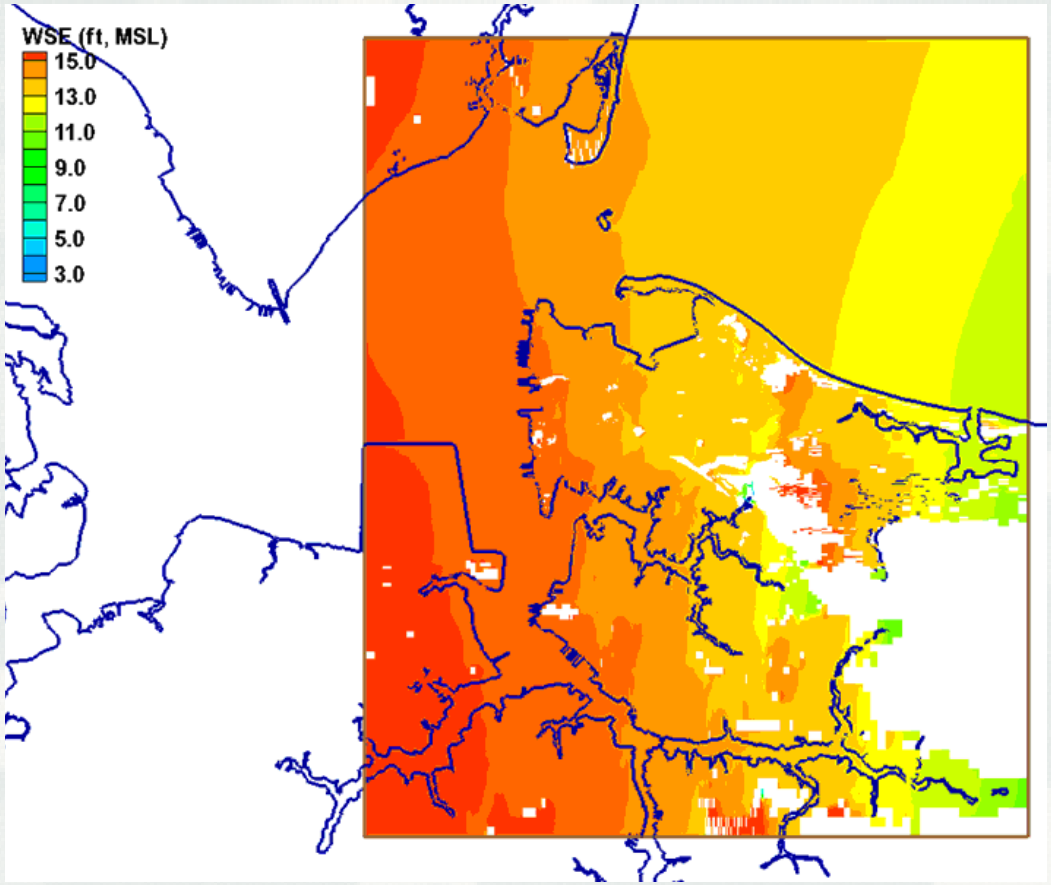


CMS Results

Water Surface Elevation (Mean Sea Level + 2 m Sea Level Rise):

Wave Height (2 m):

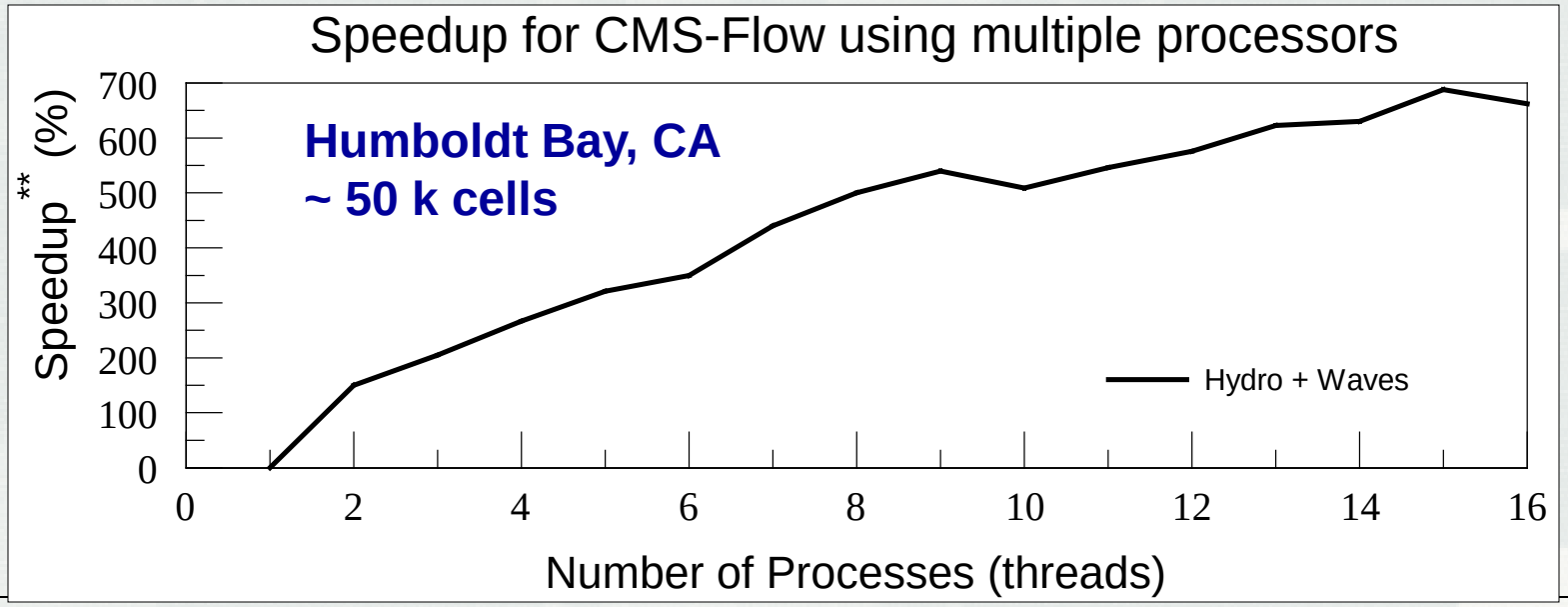
Example water level



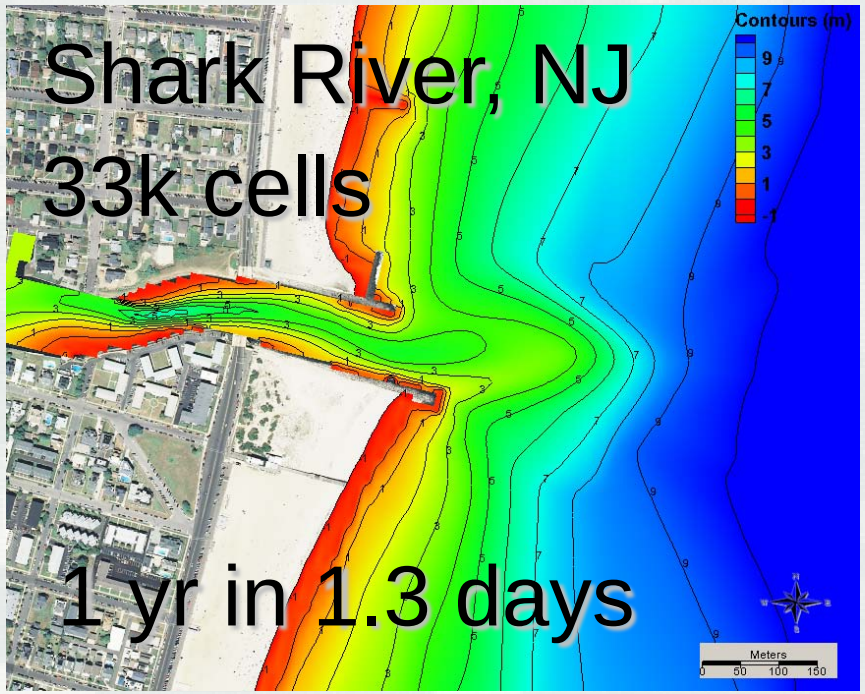
Parallel Processing (Explicit)

- **Explicit CMS-Flow parallelized using OpenMP**
  - **Ideal for multi-core machines**
- **Implicit parallelization starting using hybrid MPI and OpenMP**
- **Purchase quad and dual-quad PC's!**

$$\text{speed up} = 100 \frac{\text{Serial run time}}{\text{Parallel run time}}$$



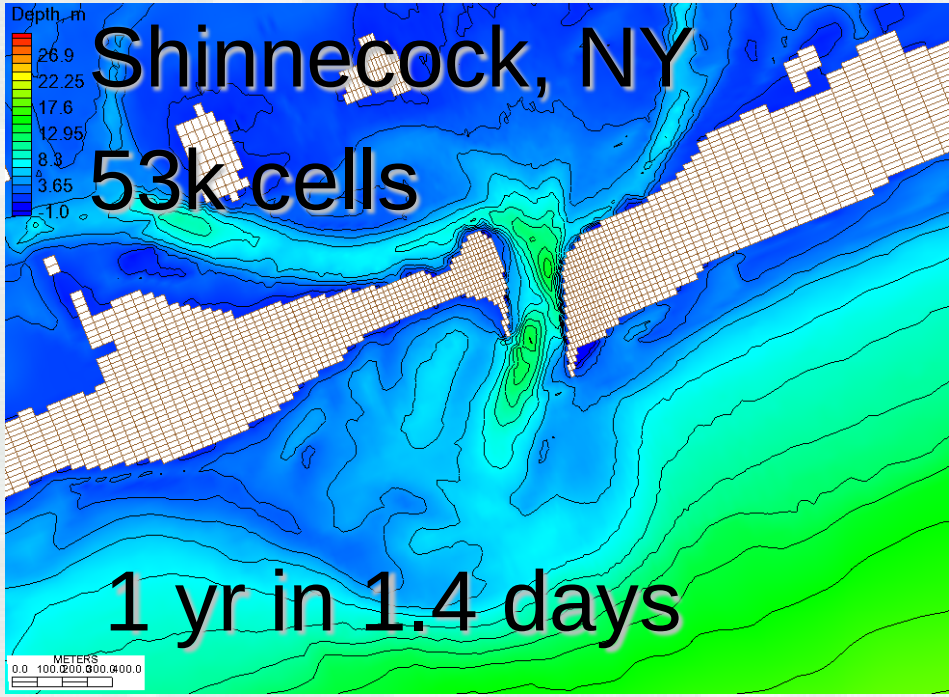
Computational Speed (Implicit)



Shark River, NJ

33k cells

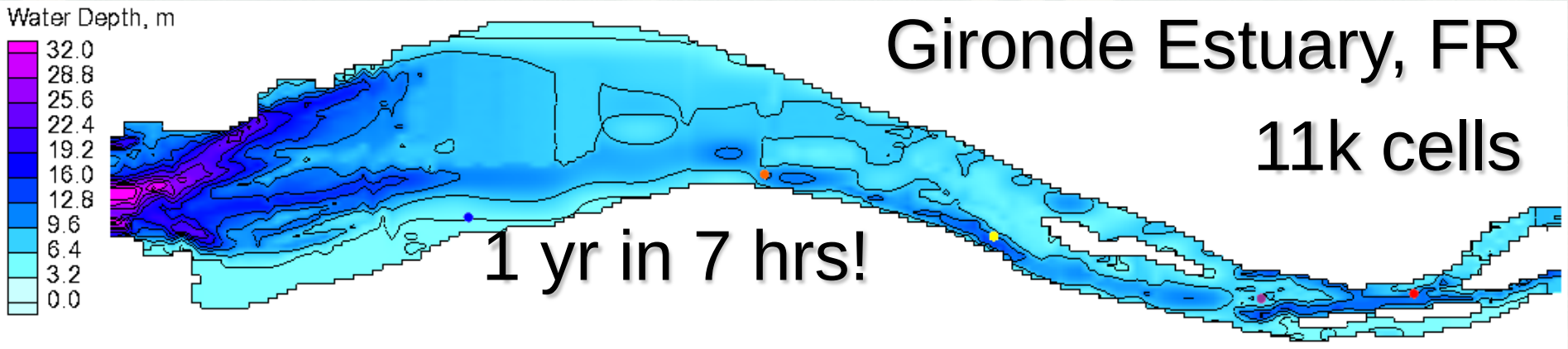
1 yr in 1.3 days



Shinnecock, NY

53k cells

1 yr in 1.4 days



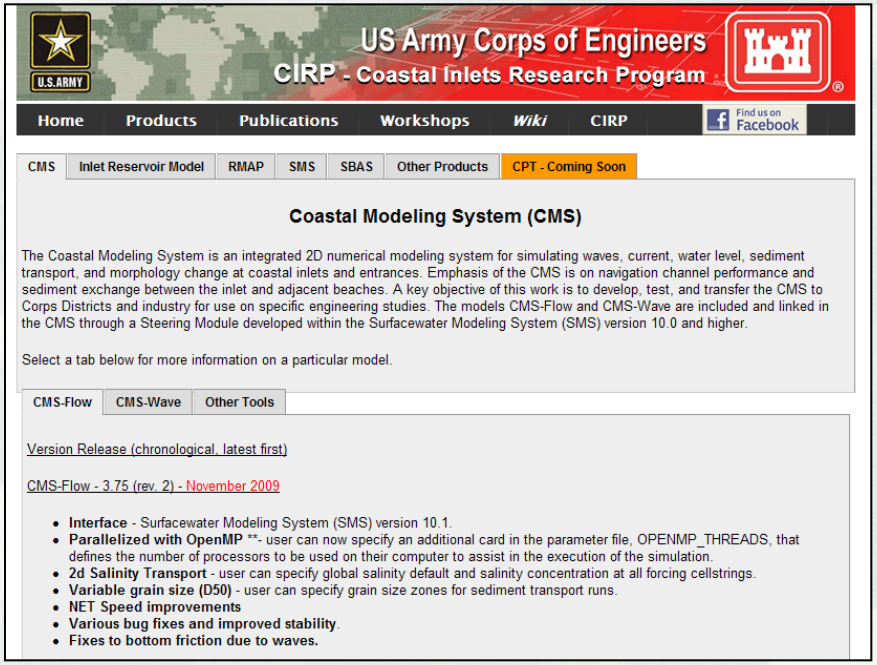
Gironde Estuary, FR

11k cells

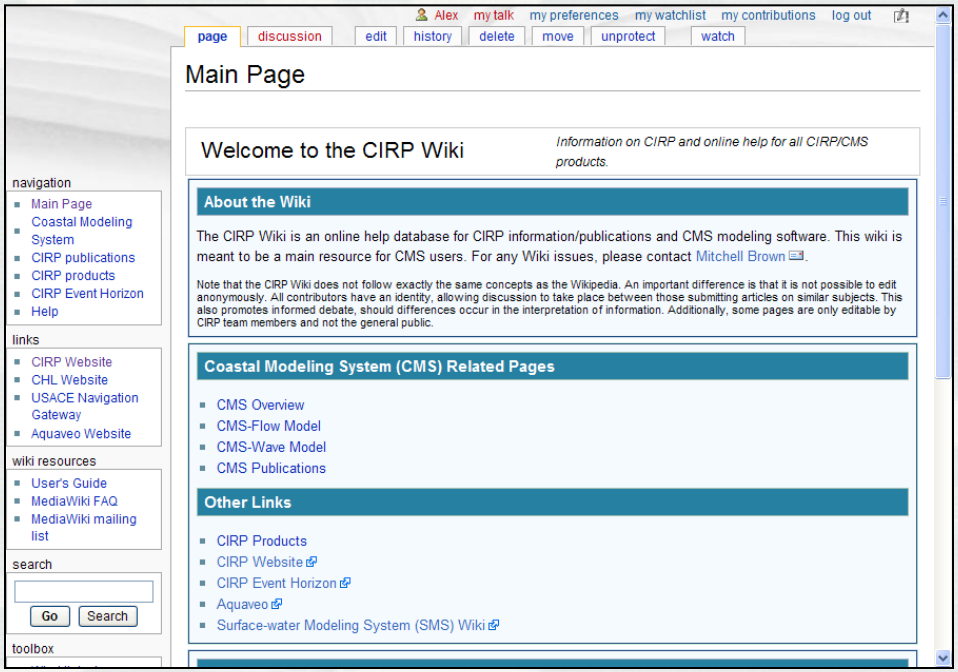
1 yr in 7 hrs!

Documentation

- CIRP website



- Wiki Website



http://cirp.usace.army.mil/

http://cirp.usace.army.mil/wiki/

Questions?

Alejandro.Sanchez@usace.army.mil

Reports and Tech Notes

- Demirbilek, Z., K. J. Connell, N. J. MacDonald, and A. K. Zundel. 2008. **Particle Tracking Model in the SMS 10: IV. Link to Coastal Modeling System,** Coastal and Hydraulics Engineering Technical Note ERDC/CHL CHETN-IV-71. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Brown, M. E., and N. C. Kraus. 2007. **Tips for developing bathymetry grids for Coastal Modeling System Applications,** Coastal and Hydraulics Laboratory Engineering Technical Note ERDC/CHL CHETN-IV-69. Vicksburg, MS: U.S. Army Engineer Research and Development Center.
- Buttolph, A. M., Reed, C. W., Kraus, N. C., Ono, N., Larson, M., Camenen, B., Hanson, H., Wamsley, T., and Zundel, A. K. 2006. **Two-Dimensional Depth-Averaged Circulation Model CMS-M2D: Version 3.0, Report 2, Sediment Transport and Morphology Change,** Technical Report ERDC/CHL-TR-06-7, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi.
- Lin, L., Z. Demirbilek, H. Mase, J. Zheng., and F. Yamada. 2008. **CMS-Wave: A Nearshore Spectral Wave Processes Model for Coastal Inlets and Navigation Projects**. ERDC/CHL TR-08-13.
- Lin, L., H. Mase, F. Yamada, and Z. Demirbilek. 2006. **Wave-Action Balance Equation Diffraction (WABED) Model: Tests of Wave Diffraction and Reflection at Inlets**. ERDC/CHL CHETN-III-73.

Publications: Sediment Transport

- Sánchez, A., and Wu, W. 2010. **"A Non-equilibrium Sediment Transport Model for Coastal Inlet Applications".** *Journal of Coastal Research*, Submitted Oct 2009.
- Camenen, B., and Larson, M., 2008. **"Equivalent Roughness Height for Plane Bed Oscillatory Flow,"***Estuarine, Coastal, and Shelf Science*, Vol 81, pp 409-422.
- Camenen, B., and Larson, M., 2008. **"A General Formula for Non-Cohesive Suspended Sediment Transport,"** *Journal of Coastal Research*, Vol 24, No. 3, pp 615-627.
- Camenen, B., and Larson, M. 2007. **"A Unified Sediment Transport Formulation for Coastal Inlet Application,"** Contract Report ERDC/CHL-CR-07-1, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi.
- Camenen, B., and Larson, M. 2007. **"A Total Load Formula for the Nearshore,"** *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 56-67.
- Hanson, H., and Camenen, B. 2007. **"Closed Form Solution for Threshold Velocity for Initiation of Sediment Motion Under Waves,"** *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 15-27.
- Camenen, B. and Larson, M., 2006. **"Phase Lag Effects in Sheet Flow Transport,"** *Coastal Engineering*,Vol 53, pp 531-542.
- Camenen, B., Bayram, A., and Larson, M., 2006. **"Equivalent Roughness Height for Plane Bed Under Steady Flow,"** *Journal of Hydraulic Engineering*,Vol 132, No. 11, pp 1146-1158.
- Gravens, M. B., and Wang, P. 2007. **"Data Report: Laboratory Testing of Longshore Sand Transport by Waves and Currents; Morphology Change Behind Headland Structures,"** Technical Report ERDC/CHL-TR-07-8, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi.

Publications: Applications/Projects

- Beck, T.M., and Wang, P. 2009. **Influences of channel dredging on flow and sedimentation patterns at microtidal inlets, West-central Florida, USA.** Proceedings Coastal Dynamics 2009.
- Li, H., Brown, M. E., Smith, T. D., Podoski, J. H., 2009 (draft). **Evaluation of Proposed Channel on Circulation and Morphology Change at Kawaihae Harbor and Pelekane Bay, Island of Hawaii, HI**, Technical Report ERDC/CHL-TR-XX-XX, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.
- Seabergh, W.C., Smith, E.R., and Rosati, J.D. 2009 (draft). **Sabine-Neches Waterway, Sabine Pass Jetty System: Past and Future Performance,** ERDC/CHL-TR-09-X, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS
- Demirbilek, Z., Lin, L., and Nwogu, O. G. 2008. **Wave Modeling for Jetty Rehabilitation at the Mouth of the Columbia River, Washington/Oregon, USA,** ERDC/CHL-TR-08-3, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi.
- Barcak, R. G., Kraus, N. C., Lin, L., Smith, E. R., Heilman, D. J., and Thomas, R. C. 2007 **Navigation Improvement, Mouth of the Colorado River, Texas,** *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 1502-1514.
- Wang, P., Tidwell, D. K., Beck, T. M., and Kraus, N. C. 2007. **Sedimentation Patterns in a Stabilized Migratory Inlet, Blind Pass**, FL. *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 1377-1390.
- Zarillo, G. A., and Brehin, F. G. A. (2007) **Hydrodynamic and Morphologic Modeling at Sebastian Inlet, FL,** *Proceedings Coastal Sediments '07 Conference*, ASCE Press, Reston, VA, 1297-1310.
- Wamsley, T. V., Cialone, M. A., Connell, K. J., and Kraus, N. C. 2006. **Breach History and Susceptibility Study, South Jetty and Navigation Project, Grays Harbor, Washington,** ERDC/CHL-TR-06-22, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.
- Hughes, S. A., and Cohen, J. 2006. **Half Moon Bay, Grays Harbor, Washington: Movable-Bed Physical Model Study,** Technical Report ERDC/CHL-TR-06-15, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

Additional Publications

- Nam, P.T., and Larson, M. 2010. **Model of nearshore waves and wave-induced currents around a detached breakwater,** Journal of Waterway, Port, Coastal, and Ocean Engineering, 136(3),156-176.
- Wu, W., Sánchez, A., and Mingliang, Z., 2010. **An Implicit 2-D Shallow Water Flow Model on an Unstructured Quadtree Rectangular Grid**, *Journal of Coastal Research*, Submitted Oct 2009
- Nam, P.T., Larson, M., Hanson, H., and Hoan, L.X. 2009. **A numerical model of nearshore waves, currents, and sediment transport,** Coastal Engineering, 56, 1084-1096.
- Demirbilek, Z., Lin, L., Seabergh, W.C., Mase, H., and Zheng, J.I. 2009. **Laboratory and Numerical Studies of Hydrodynamics Near Jetties,** *Coastal Engineering Journal* Vol. 51, No. 2, 143-175.
- Sánchez, A. 2008. ***Interactions between wetlands and tidal inlets,*** Coastal andHydraulics Engineering Technical Note. ERDC/CHL CHETN-IV-72. Vicksburg,MS: U.S. Army Engineer Research and Development Center.
- Seabergh, W. C., Demirbilek, Z., and Lin, L. (2008). **Guidelines Based on Physical and Numerical Modeling Studies for Jetty Spur Design at Coastal Inlets,** *International Journal of Ecology & Development (IJED)*, Vol. 11, No. F08, pp 4-19.
- Zheng, J., H. Mase, Z. Demirbilek, and L. Lin. 2008. **Implementation and evaluation of alternative wave breaking formulas in a coastal spectral wave mode**. *Ocean Engineering*. Vol. 35., pp.1090-1101.
- MacDonald, N. J., Davies, M. H., Zundel, A. K., Howlett, J. D., Demirbilek, Z., Gailani, J. Z., Lackey, T. C., and Smith, J. (2006). **PTM: Particle Tracking Model; Report 1: Model Theory, Implementation, and Example Applications,** Technical Report ERDC/CHL-TR-06-20, US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, Mississippi.

Eddy Viscosity

- Sum of
  - Kinematic viscosity
  - Wave-related component
    - Kraus and Larson (1991)
  - Current-related component
    - Falconer (1980) equation
    - Parabolic model
    - Subgrid model (default)
    - Mixing length model
- Options can be changed through advanced cards

$$\nu_t = \nu_0 + \nu_c + \nu_w$$

$$\nu_w = \Lambda u_w h$$

$$\nu_c = \sqrt{\left(c_0 u_{*c} h\right)^2 + \left(c_1 \left|\bar{S}\right|\right)^2}$$

$$\left|\bar{S}\right| = \sqrt{2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)^2}$$

$$\text{Falconer: } c_0 = 0.578 c_b,\ c_1 = 0$$

$$\text{Parabolic: } c_1 = 0$$

$$\text{Subgrid: } c_1 = c_m \bar{\Delta}$$

$$\text{Mixing length: } c_1 = \left[\kappa \min\left(c_m h, y'\right)\right]^2$$

Mean bottom shear stress

- Currents only
  - Quadratic formula

$$\tau_m = \tau_c = \rho c_b u_c^2$$

- Waves and currents
  - Simplified quadratic formula with added shear from bottom wave orbital velocity (default)

$$\tau_m = \rho c_b u_c \sqrt{u_c^2 + 0.5 u_w^2}$$

  - Soulsby (1995) 2 and 13 coefficient data fit formulas

$$\tau_m = \lambda_{wc} \tau_c$$

  - Fredsoe (1984)
  - Huynh-Thanh and Temperville (1991)

$$\lambda_{wc} = 1 + bX^p (1 - X)^q, \; X = \frac{\tau_w}{\tau_c + \tau_w}$$

$$b, p, q = f\left(c_b, f_w, \phi\right)$$

$$\tau_w = 0.5 \rho f_w u_w^2$$

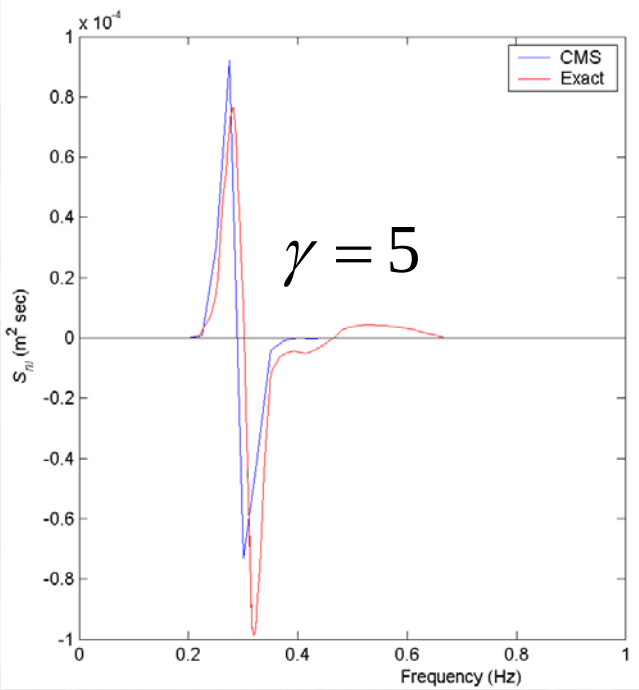
- Options can be changed in advanced cards

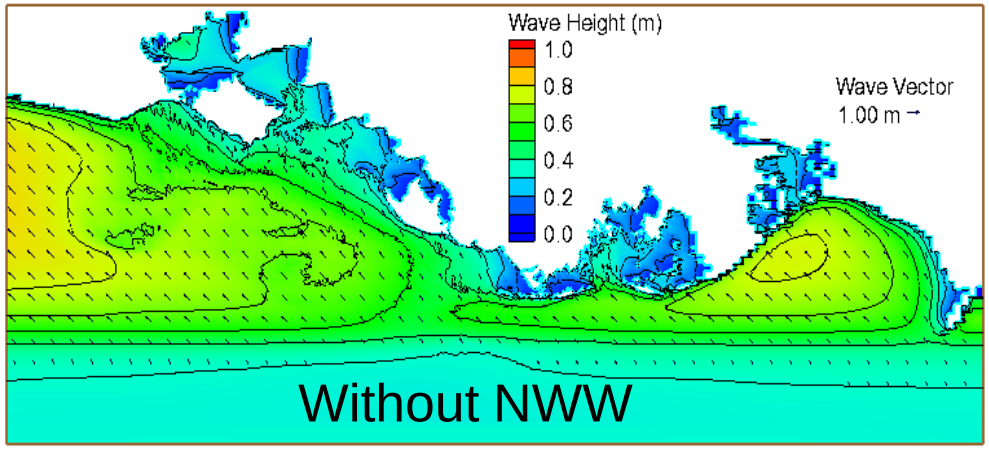
Nonlinear Wave-Wave Interaction

$$S_{nl} = a(\sigma)\frac{\partial B}{\partial \sigma} + b(\sigma)\frac{\partial^2 B}{\partial \theta^2}$$ (Jenkins & Phillips, 2001)

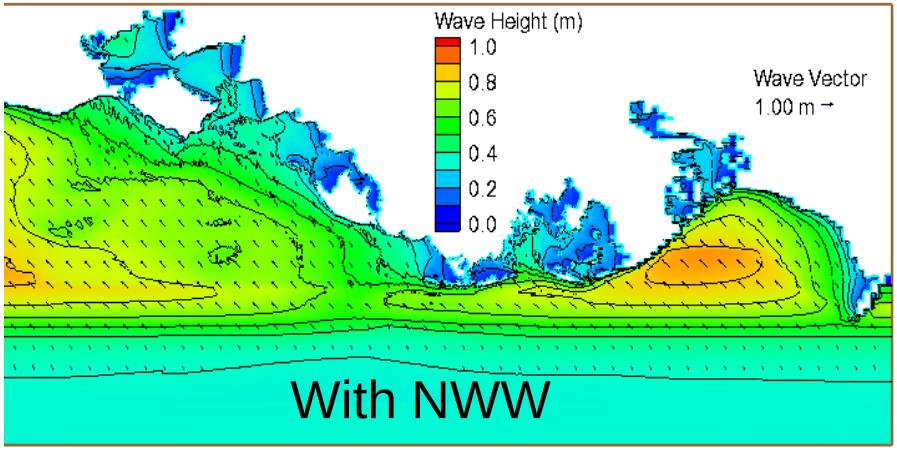
$$B = k^3\sigma^5 \frac{n^4}{(2\pi)^2 g}\left[\left(\frac{\sigma_o}{\sigma}\right)^4 E\right]^3$$

$$a = \frac{1}{2n^2}[1+(2n-1)^2\cosh 2kh]-1 \qquad b = \frac{a}{n\sigma}$$





Without NWW



With NWW

Wave-current Interaction

- Dispersion equation

$$\sigma = \sqrt{gk \tanh kh} + k_i u_i$$

- Characteristic velocities

$$c_i = c_{gi} + u_i \qquad c_\theta = \frac{\sigma}{\sinh 2kh}\left(\sin\theta \frac{\partial h}{\partial x} - \cos\theta \frac{\partial h}{\partial y}\right)$$

$$+\frac{\sin 2\theta}{2}\frac{\partial u}{\partial x} - \cos^2\theta \frac{\partial u}{\partial y} + \sin^2\theta \frac{\partial v}{\partial x} - \frac{\sin 2\theta}{2}\frac{\partial v}{\partial y}$$

- Wave radiation stress gradients

$$\tau_{Si} = -\frac{1}{\rho}\frac{\partial S_{ij}}{\partial x_j} \qquad S_{ij} = E\left[n\frac{k_i k_j}{k^2} + \delta_{ij}\left(n - \frac{1}{2}\right)\right] \qquad n = \frac{1}{2} + \frac{kh}{\sinh 2kh}$$

- Plus eddy viscosity and bottom shear stress

Sediment Transport

Equilibrium Total-Load Transport Model

- Assumes both the bed and suspended loads are in local equilibrium at all times
- Solves the Exner Equation (sediment mass balance equation)

$$(1-p'_m)\frac{\partial \zeta}{\partial t} = \frac{\partial q_{t*j}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[D_s \left|q_{t*}\right| \frac{\partial \zeta}{\partial x_j}\right]$$

$D_s \rightarrow$ Bed-slope coefficient

$p'_m \rightarrow$ Sediment porosity

$q_{t*} \rightarrow$ Equilibrium total load sediment transport

$\zeta \rightarrow$ Still water depth

Sediment Transport

Equilibrium Bed-Load /AD Suspended-Load Model

- Assumes
  - Bed load is in local equilibrium
- Solves
  - AD equation for suspended concentration

$$\frac{\partial(hC)}{\partial t}+\frac{\partial(u_j hC)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[Kh\frac{\partial C}{\partial x_j}\right]+P-D$$

  - Sediment balance equation for bed change rate

$$(1-p'_m)\frac{\partial\zeta}{\partial t}=\frac{\partial q_{b*j}}{\partial x_j}+\frac{\partial}{\partial x_j}\left[D_s\left|q_{t*}\right|\frac{\partial\zeta}{\partial x_j}\right]+P-D$$

$U \rightarrow$ Depth-averaged current velocity

$h \rightarrow$ Total water depth

$D \rightarrow$ Deposition rate

$K \rightarrow$ Diffusion coefficient

$P \rightarrow$ Erosion rate (pick-up)

$q_{b*} \rightarrow$ Equilibrium bed load

Sediment Transport

Non-equilibrium Sediment Transport Model (New)

- Adopts
  - Adaptation concept
- Solves
  - AD equation for total load concentration

$C_t \rightarrow$ Total load concentration

$\beta_t \rightarrow$ Transport correction factor

$r_s \rightarrow$ Fraction of suspended load

$\alpha_t \rightarrow$ Adaptation coefficient

$\omega_f \rightarrow$ Fall velocity

$$\frac{\partial}{\partial t}\left(\frac{hC_t}{\beta_t}\right)+\frac{\partial\left(u_j hC_t\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left[Kh\frac{\partial\left(r_s C_t\right)}{\partial x_j}\right]+\alpha_t\omega_f\left(C_{t*}-C_t\right)$$

  - Sediment balance equation for bed change rate

$$(1-p_m^{'})\frac{\partial\zeta}{\partial t}=\alpha_t\,\omega_f\,(C_{t*}-C_t)+\frac{\partial}{\partial x_j}\left[D_s\left|q_b\right|\frac{\partial\zeta}{\partial x_j}\right]$$