CMS Sediment Transport and Morphology Change Capabilities

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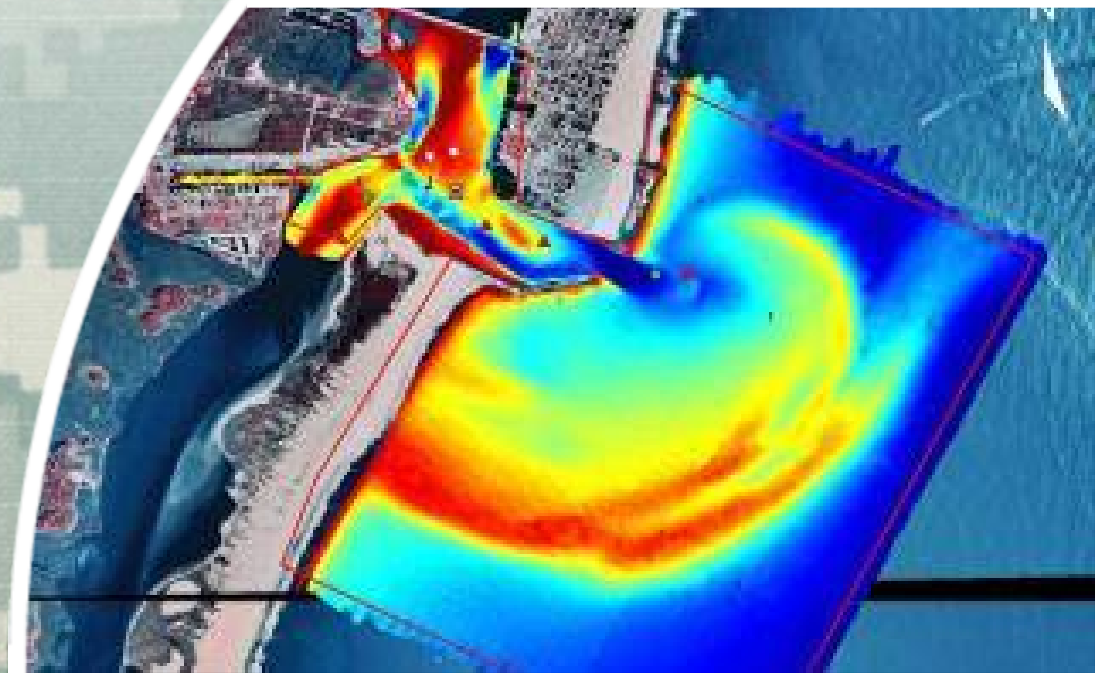

US Army Corps of Engineers

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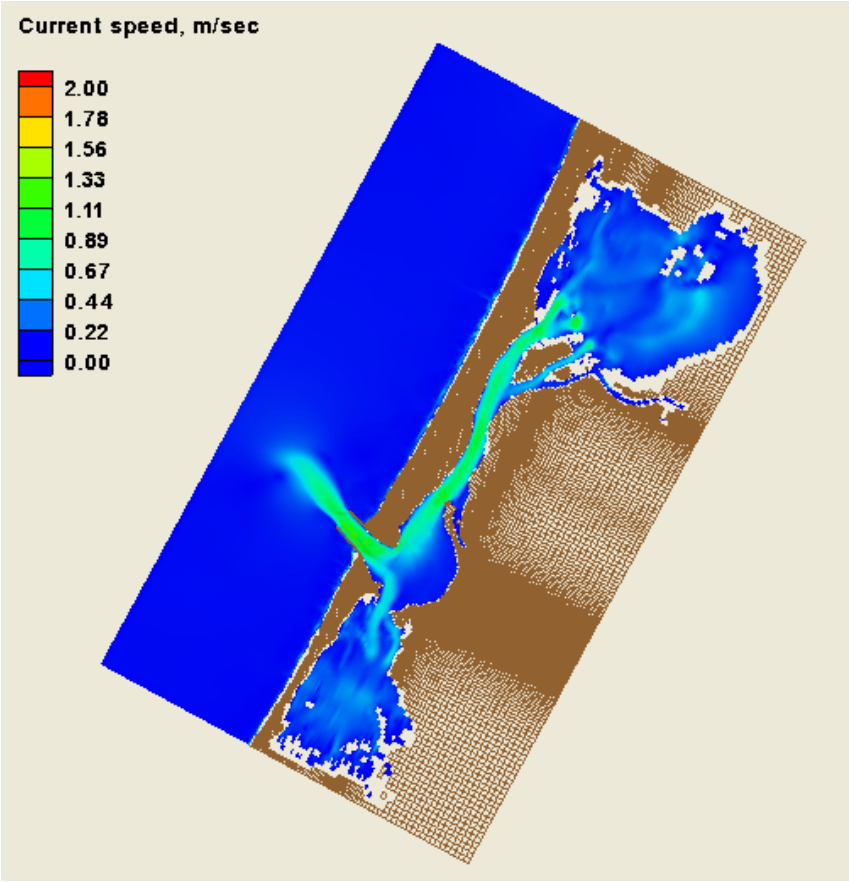
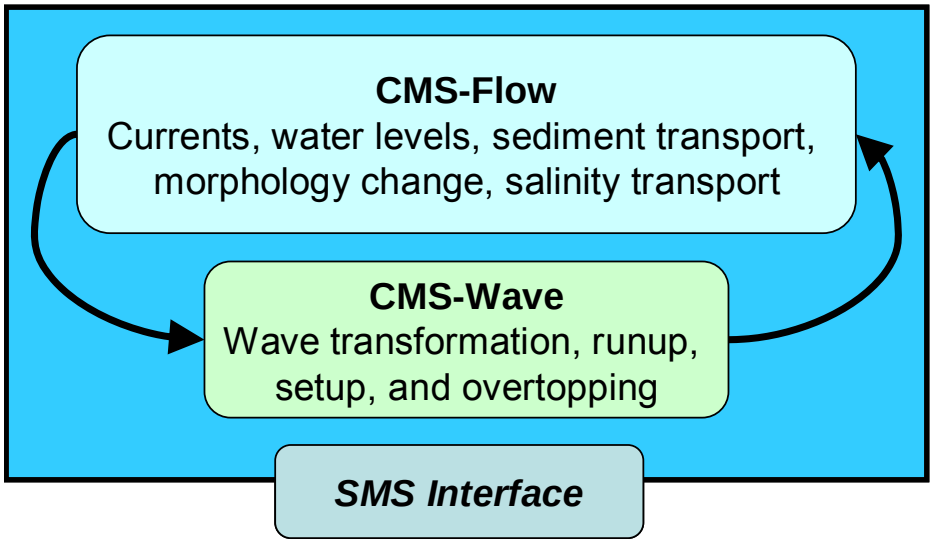
Outline

1. Introduction
2. Key features
3. Sediment transport models
4. Sediment transport formulas
5. Avalanching
6. Hiding and exposure
7. Model parameters
8. Validation, applications and sensitivity analysis
9. Ongoing R&D activity



1. Introduction



- Sediment transport is calculated in CMS-Flow on the same grid as the hydrodynamics (inline code)
- Time steps for sediment transport and morphology change do not have to be the same as for the hydro calculation

2. Key features

- Sediment transport models
  - Equilibrium Total Load (Exner equation)
  - Equilibrium Bed Load + Advection-Diffusion Suspended Load
  - Non-Equilibrium (Advection-Diffusion Total Load)
- 3 sediment transport formulas
  - Lund-CIRP (ERDC/CHL CR-07-01)
  - Van Rijn (J. Hydraulic Eng. 2007)
  - Watanabe (Proc. Coastal Sediments 1987)
- Hard-bottom
- Avalanching
- Bed slope
- Hiding and exposure

3. Sediment transport models (1 of 4)

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)

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

$D_s \rightarrow$ Bed-slope coefficient

$p'_m \rightarrow$ Sediment porosity

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

$\zeta \rightarrow$ Still water depth

Equilibrium Bed-Load /AD Suspended-Load Model

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

$U \rightarrow$ Depth-averaged current velocity

$h \rightarrow$ Total water depth

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

$D \rightarrow$ Deposition rate

$K \rightarrow$ Diffusion coefficient

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

  - Sediment balance equation for bed change rate

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

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

Non-equilibrium Sediment Transport Model (New)

- Adopts
  - Sediment transport 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

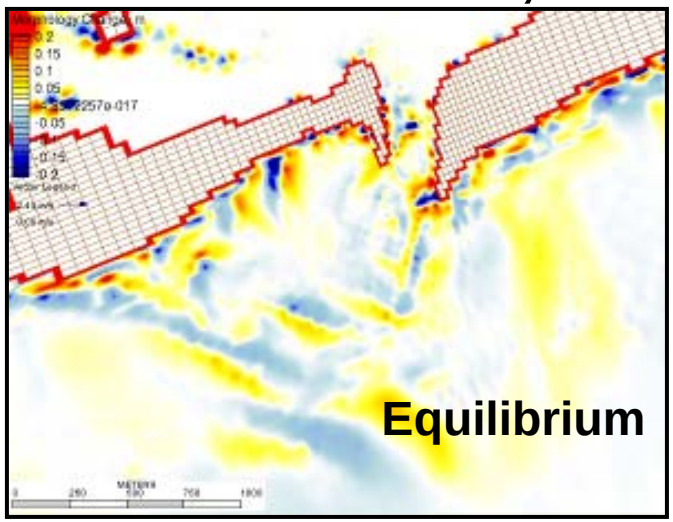
$$(1-p_m^{'})\frac{\partial\zeta}{\partial t}=\alpha_t\,\omega_f\,(C_{t*}-C_t)+\frac{\partial}{\partial x_j}\left[D_s\left|q_b\right|\frac{\partial\zeta}{\partial x_j}\right]$$

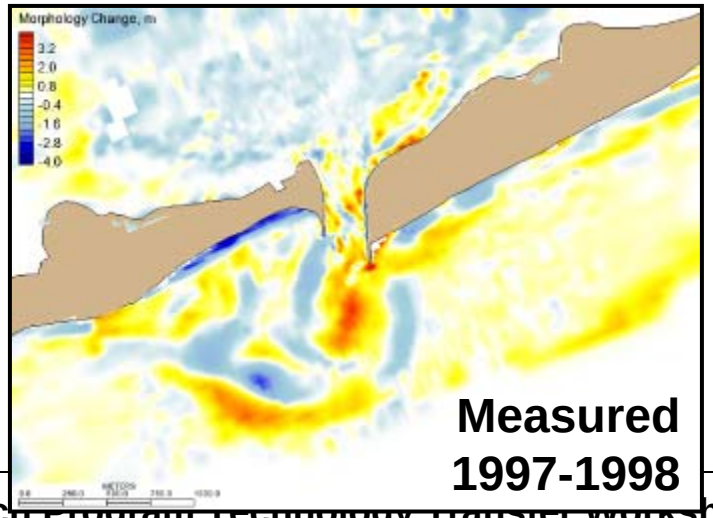
3. Sediment transport models (4 of 4)

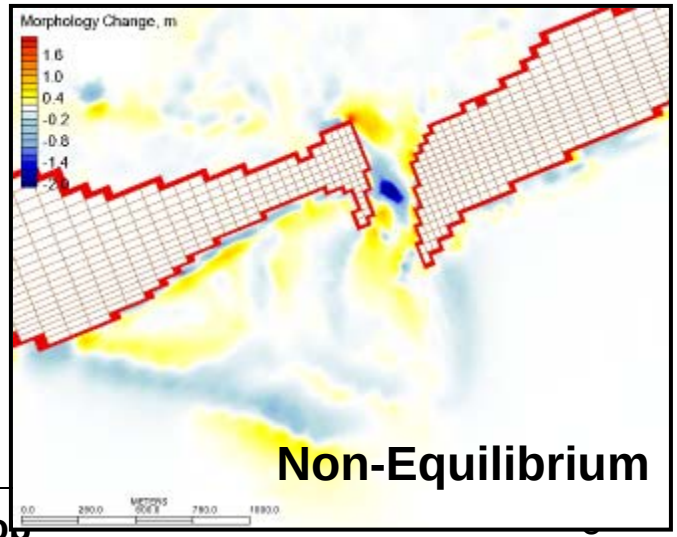
Advantages of NET

- Accounts for temporal and spatial lags between flow and sediment transport (typically reduces transport and smoothes in a physically correct way)
- Hard-bottom automatically represented
- More realistic results
- More stable

Shinnecock Inlet, NY







4. Sediment transport formulas

- "Driving force"
  - Controls largely the magnitude and distribution of the sediment concentration field and morphology change
- Represent the sediment transport under equilibrium conditions
- Available sediment transport capacity formulas in CMS:
  - Lund-CIRP (ERDC/CHL CR-07-01)
    - Separate equations for suspended and bed loads
  - Van Rijn (J. Hydraulic Eng. 2007)
    - Separate equations for suspended and bed loads
  - Watanabe (Proc. Coastal Sediments 1987)
    - One equation for total load
- Transport scaling factors are directly multiplied by values given by formulas

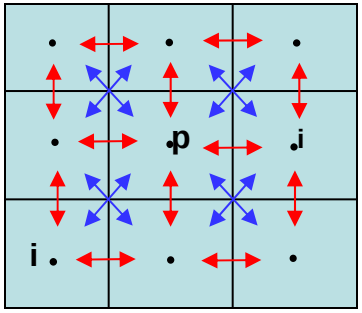
5. Avalanching

- Avalanching process simulated by enforcing

$$\left|\phi_i\right| \le \phi_r$$

$\phi \rightarrow$ Bed slope

$\phi_r \rightarrow$ Repose angle



while maintaining mass conservation between adjacent cells

- Relaxation approach- fast, stable, and efficient

$$\Delta\zeta_p^a = R\sum_i \frac{A_i \delta x_i \left(\tan\phi_i - \operatorname{sgn}\phi_i \tan\phi_r\right)}{A_p + A_i} \mathrm{H}\left(\left|\phi_i\right| - \phi_r\right)$$

- Bed update

$$\zeta_p^{n+1} = \zeta_p^n + \Delta\zeta_p^a$$

- Operates on morphologic time step
- 9- and 5-point avalanching (9 default)

$R \rightarrow$ Relax coeff.

$A \rightarrow$ Cell area

$\delta x \rightarrow$ Cell-center distance

6. Hiding and exposure

- Hiding
  - Smaller particles are sheltered from the flow by larger particles and less easily picked up from the bed
- Exposure
  - Larger particles are exposed to the flow and picked up more easily
- Current approach (phase 1) considers hiding and exposure in a single sized sediment transport model by assuming
  - Bed material composition is constant in time
  - Only one sediment size is transported
- Critical shear stress (Shields parameter)

$$\Theta_{ck}^{he} = \xi_k \Theta_{ck}$$

$\xi_k \rightarrow$ Correction factor

$\Theta_{ck} \rightarrow$ Shields parameter

$\Theta_{ck}^{he} \rightarrow$ Corrected shields parameter

$$\xi_k = \left(\frac{d_k}{d_{50}} \right)^{-m}$$

$d_k \rightarrow$ Transport grain size

$d_{50} \rightarrow$ Median grain size

$m \rightarrow$ Empirical coeff. (0.5-1)

7. Model parameters (1 of 2): Adaptation coefficient

- Related to how much time/distance it takes to reach equilibrium
- The larger the coefficient the more rapid the system goes into equilibrium and the larger the erosion and deposition

$$E - D = \alpha\, w_f (C_{t*} - C_t)$$

- Total load

$$\alpha_t = \frac{U_c\, h}{L_t\, \omega_f}$$

$$L_t = \begin{cases} (1 - r_s) L_b + r_s L_s \\ \max(L_b, L_s) \\ L_{t,given} \end{cases}$$

$L_{t,given}$ → Preferred Method

  - Suspended Load
    - Lin (1984)
    - Amanini and Silvio (1986)
  - Bed Load

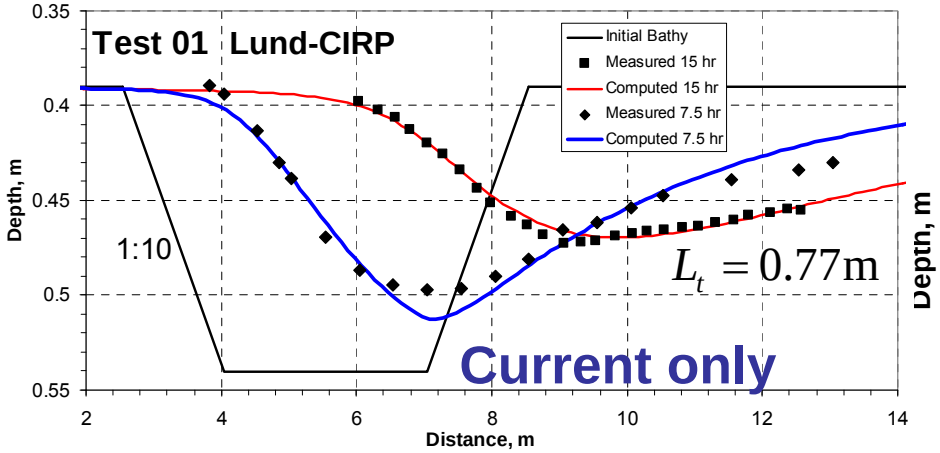
$$L_b = \begin{cases} A_{given} h \\ L_{b,given} \end{cases}$$

7. Model parameters (2 of 2): Understanding their effects

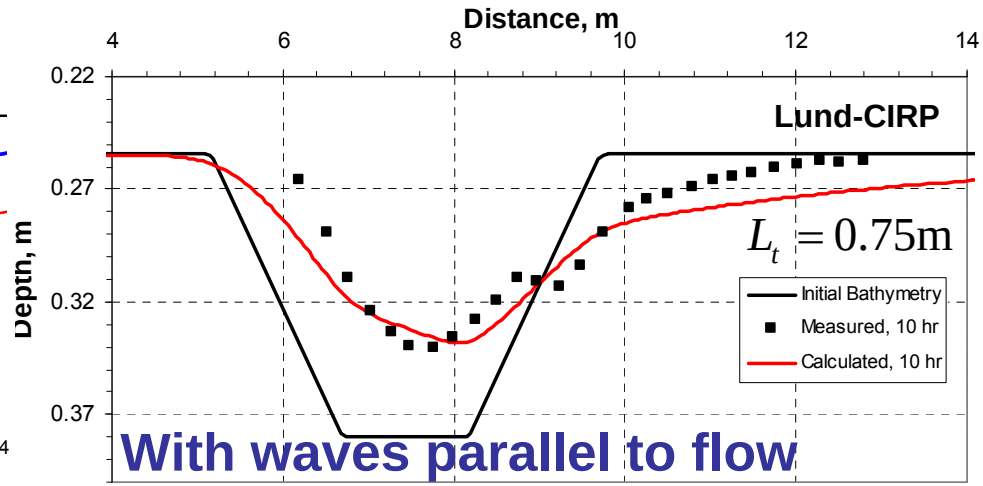
- Adaptation coefficient
  - Larger values increase local erosion or deposition and shorten the response time of the sediment concentration field to varying flow conditions
- Transport scaling factors
  - Larger values produce larger sediment loads and in turn increases morphology change
- Bed-slope coefficient
  - Larger values produce a smoothing of the morphology change
- Morphologic acceleration factor
  - Not for calibration
  - Used to reduce simulation time

$$f_{morph} = \frac{t_{\text{simulated}} + t_{\text{extrapolate}}}{t_{\text{simulated}}}$$

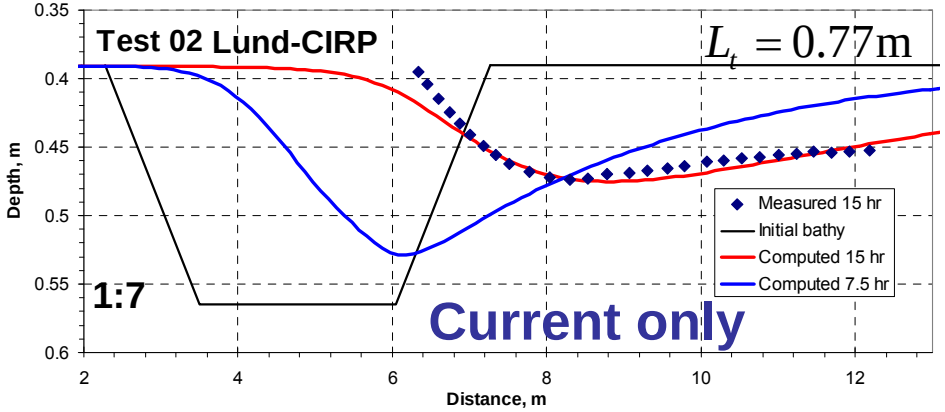
8. Validation (1 of 3): Channel Infilling (NET)



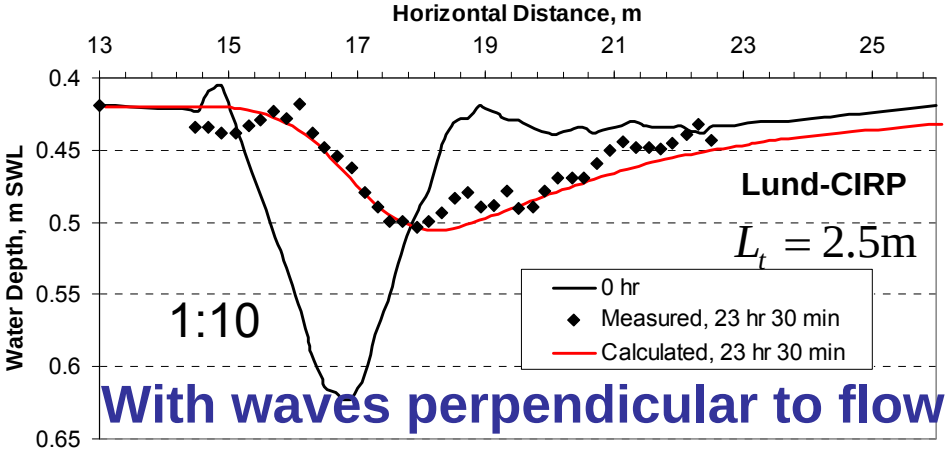
Galappatti and Vreugdenhil (1985)



Van Rijn (1985)

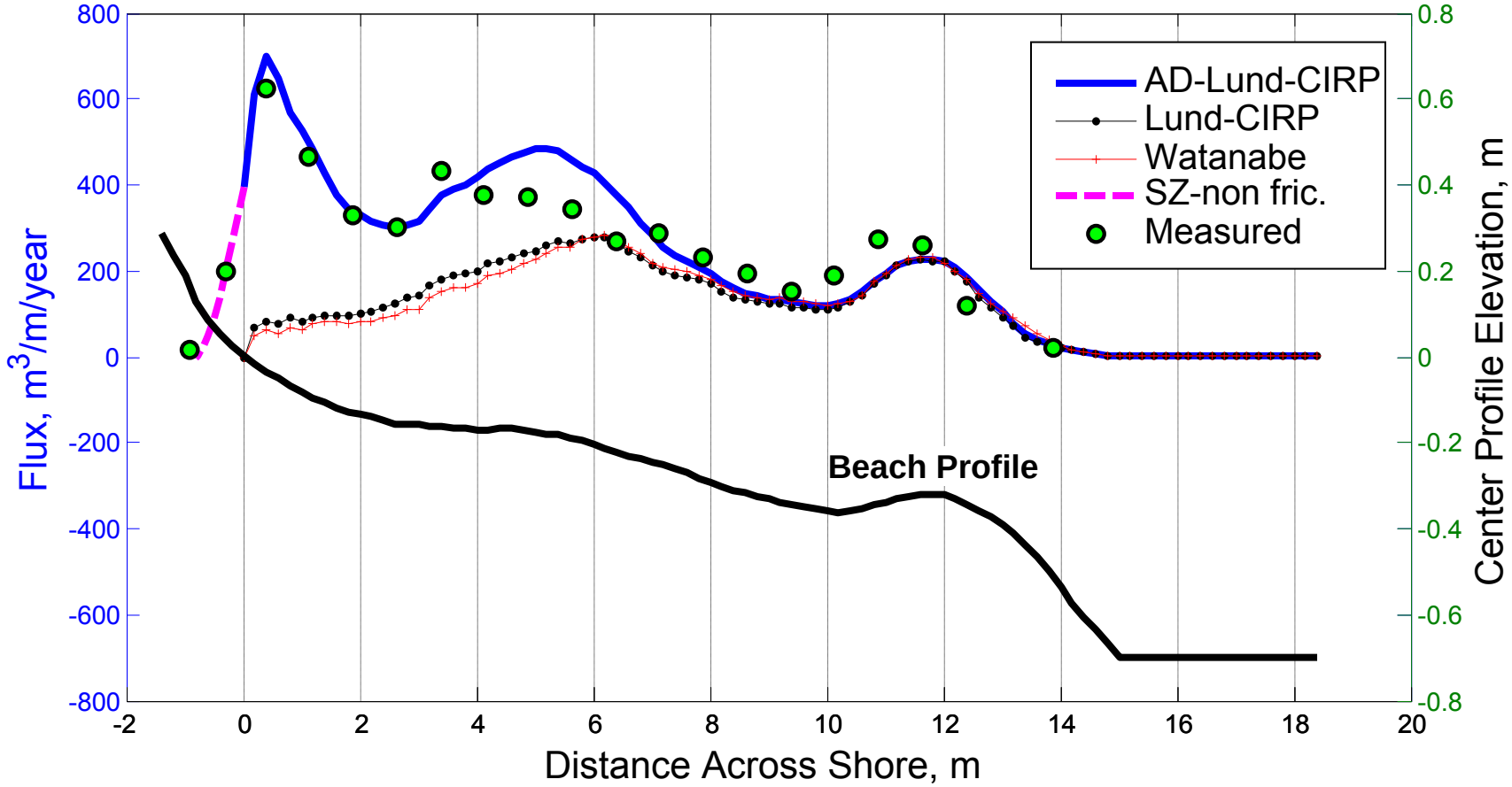


Galappatti and Vreugdenhil (1985)



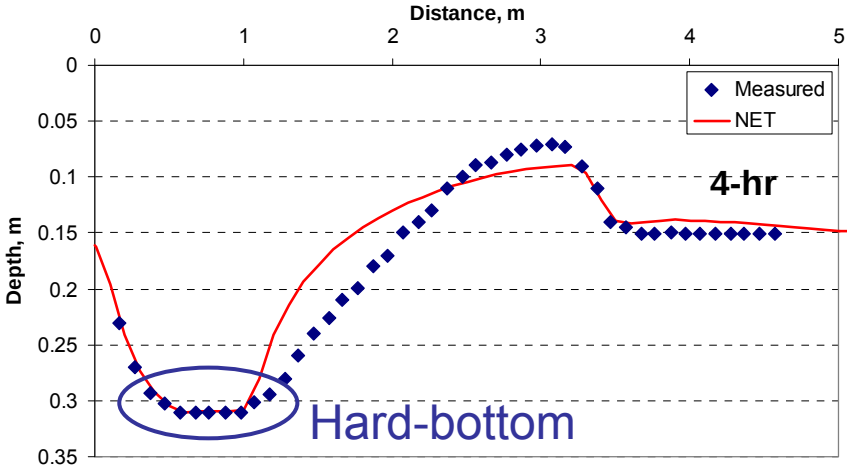
Van Rijn and Havinga (1995)

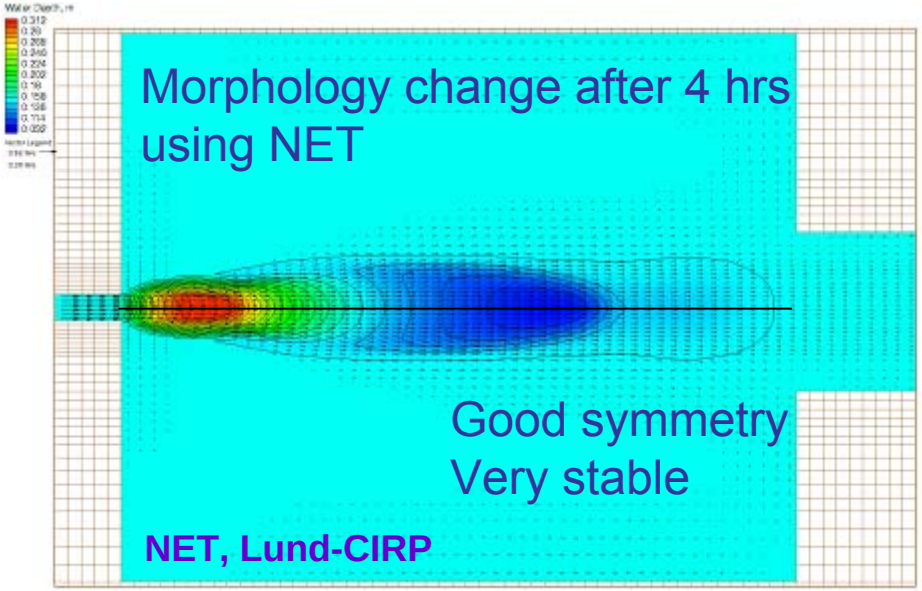
8. Validation (2 of 3): LSTF Data



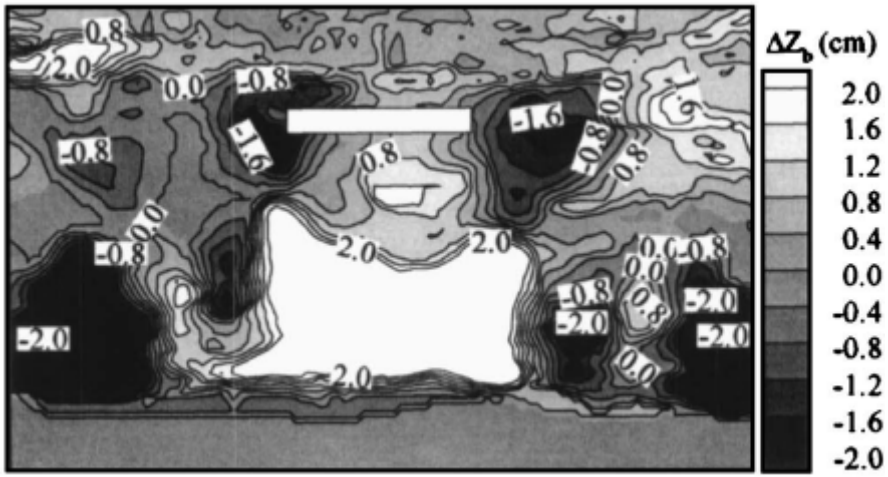
8. Validation (3 of 3)

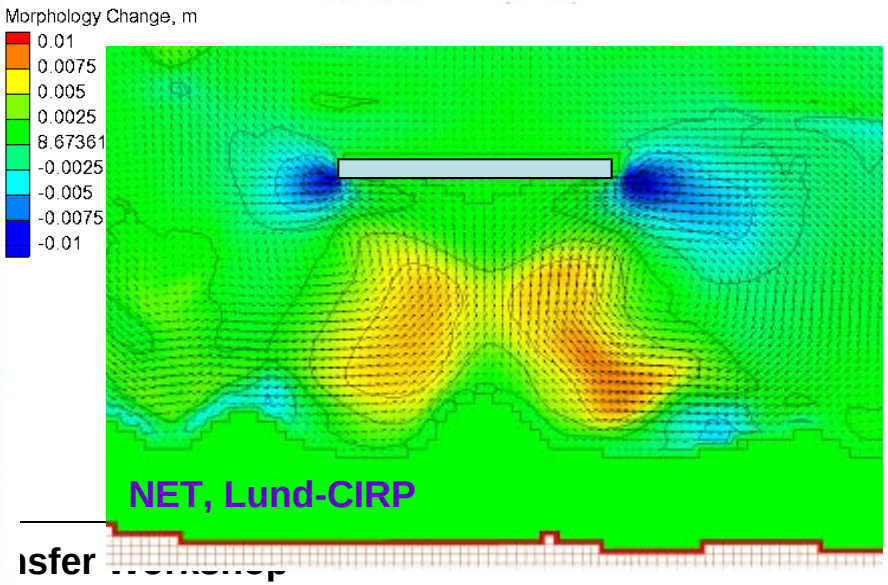
Clear-water Jet (Thuc 1991)





Detached breakwater (Mimura 1983)





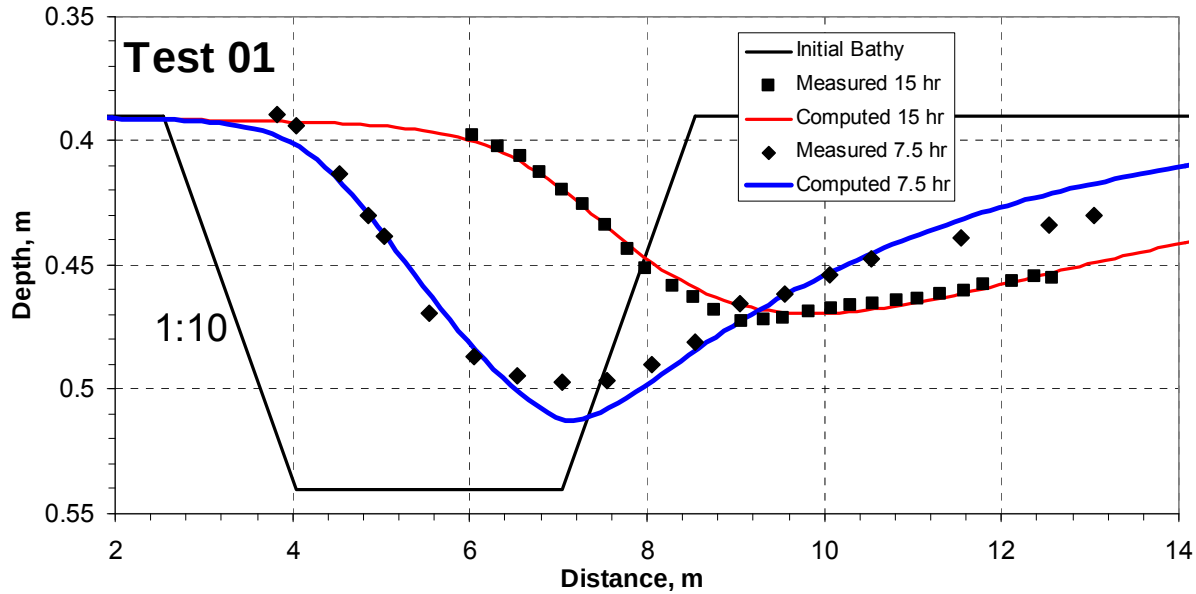
8. Sensitivity Analysis (1 of 2): Channel infilling - Calibrated Result

- Slope 1:10 (no flow separation)
- For simplicity, only the total load adaptation length is used for calibration
- Model parameters

Flow at inlet:

Current speed = 0.51 m/sec (Extreme!)

Water depth = 0.39 m



Adaptation length $L_t = 0.77$

Bed-slope coefficient $D_s = 1.0$ (default)

Suspended load scaling factor $f_s = 1.3$ (using measured susp. conc.)

Bed load scaling factor $f_b = 0.55$

8. Sensitivity Analysis (2 of 2): Channel Infilling

- Runs

  $R1 \rightarrow \alpha \times 2$

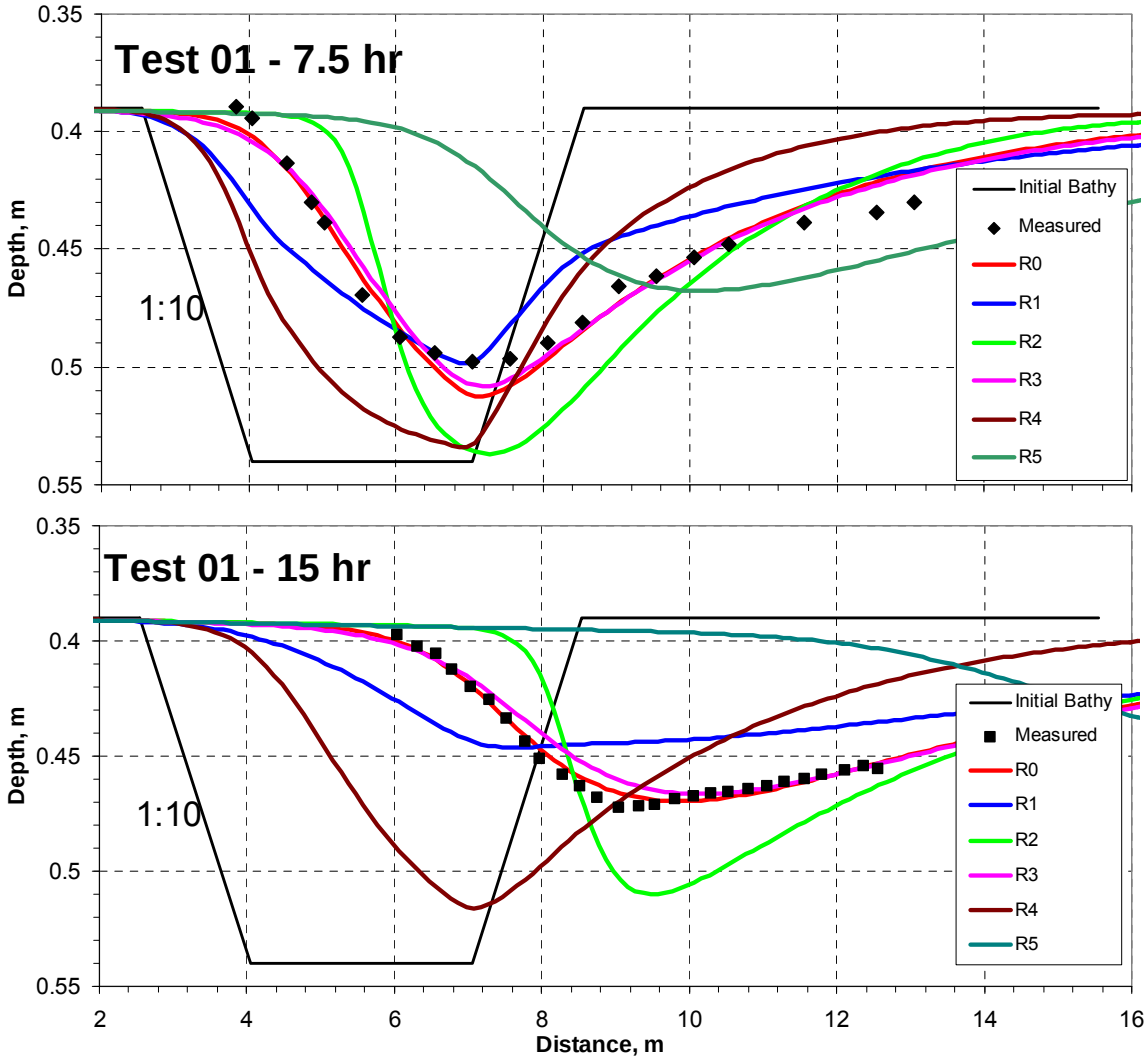
  $R2 \rightarrow \alpha \times 1/2$

  $R3 \rightarrow D_s \times 5$

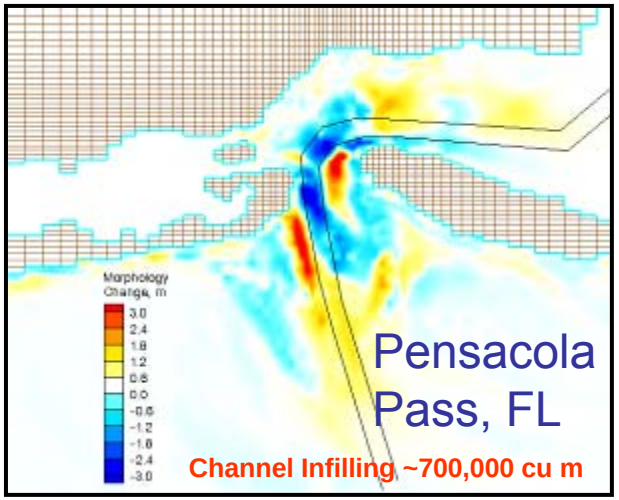
  $R4 \rightarrow (f_s, f_b) \times 1/2$

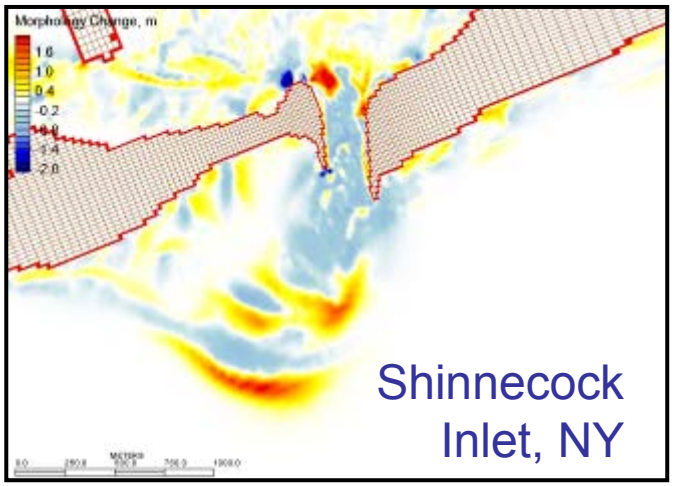
  $R5 \rightarrow (f_s, f_b) \times 2$

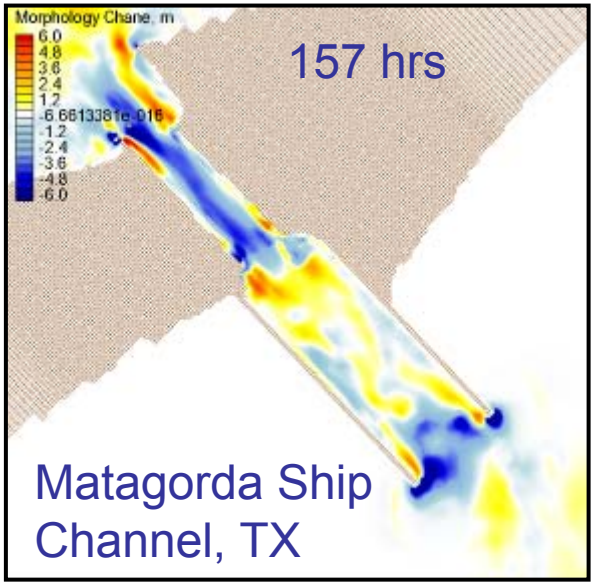
- Adaptation length affects the distance at which the sediment is deposited
- Bed-slope term fills-in troughs therefore smoothing morphology
- Morphology change directly proportional to scaling factors

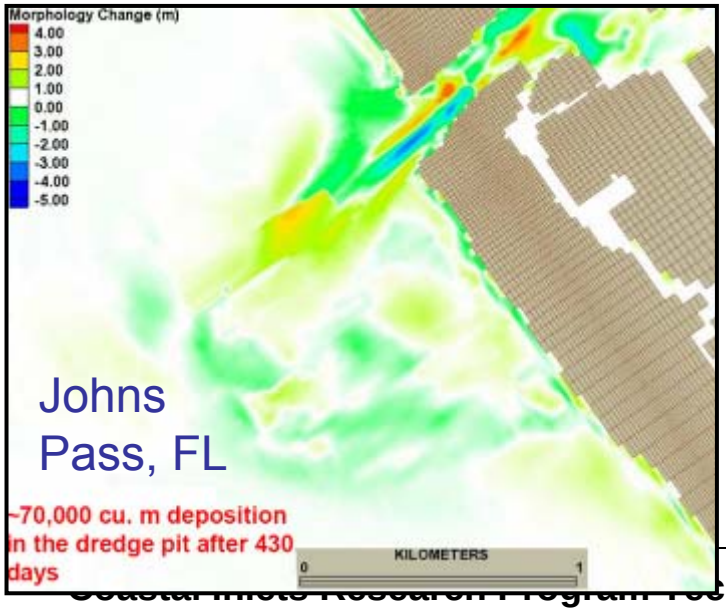


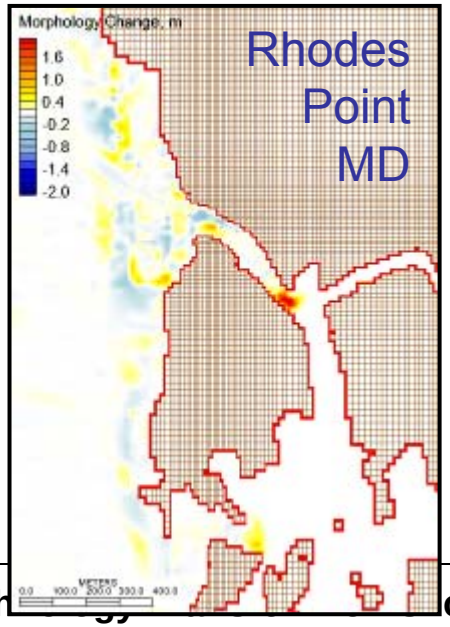
8. Applications (1 of 2)

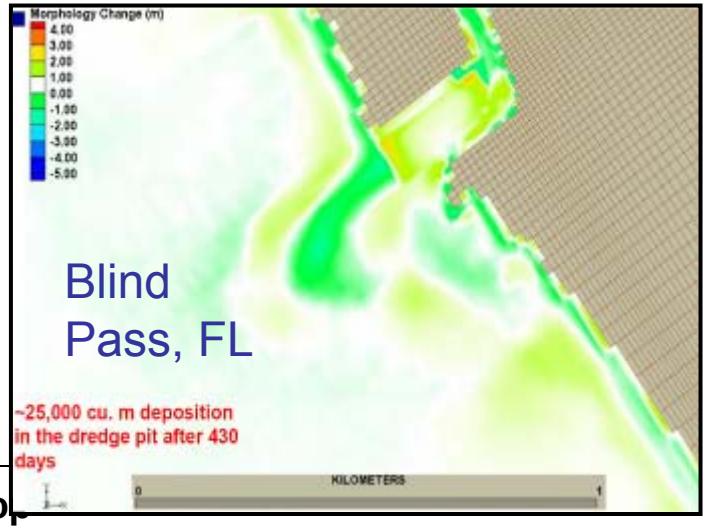




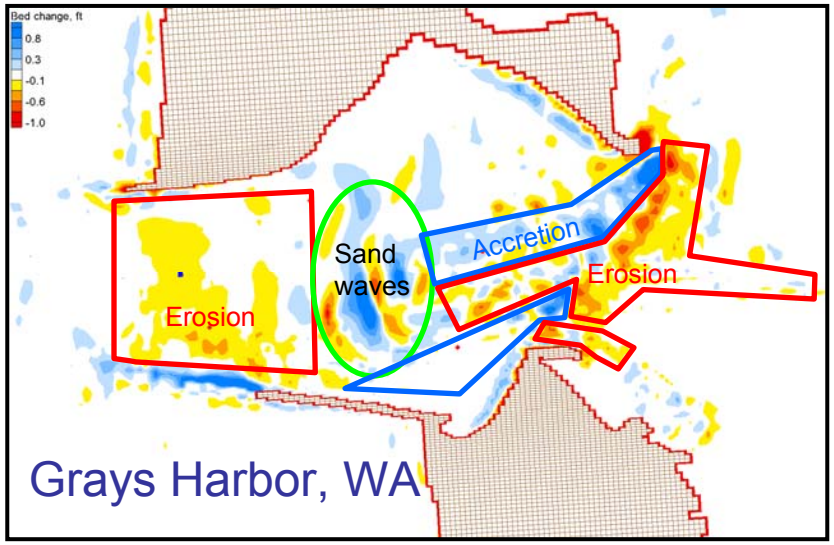


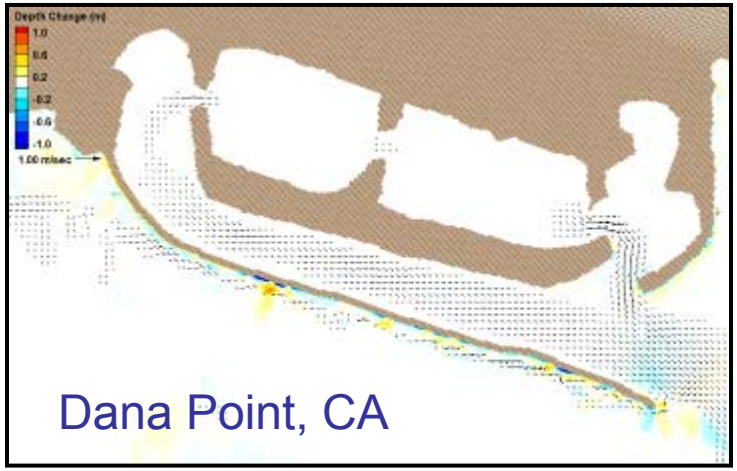


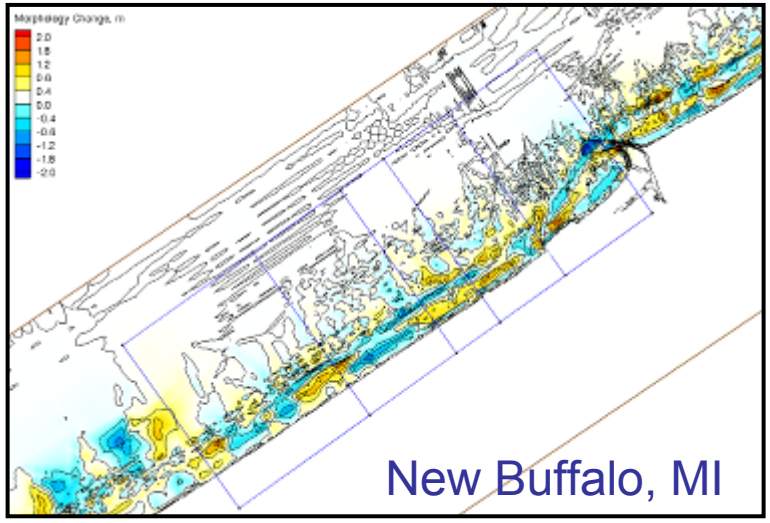


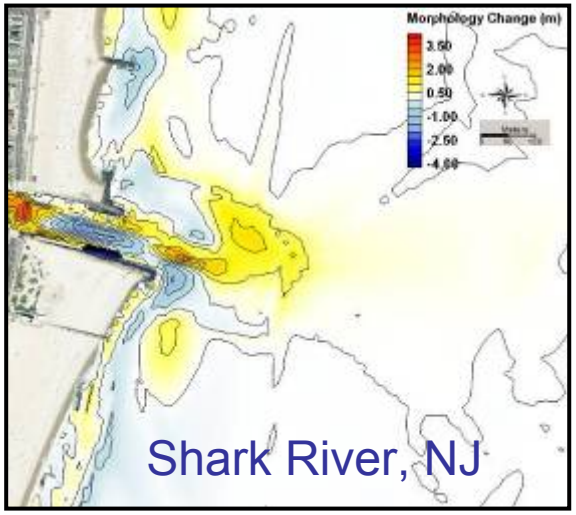


8. Applications (2 of 2)





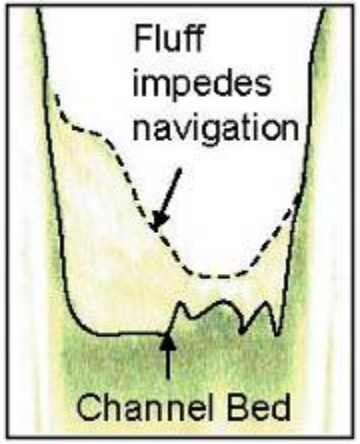
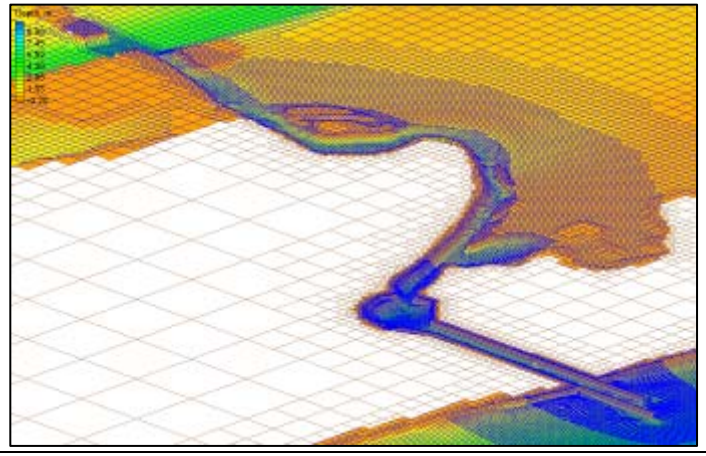




Plus…

- Ocean City, MD
- Kawaihae Hbr, HI
- Moriches, NY
- Rudee, VA
- Packery Ch, TX and elsewhere …

5. Ongoing R&D Activity

- Multiple grain sizes - hiding/exposure, armoring, bed sorting/layering
- Cohesive sediment transport for navigation channels
- Rapid Analysis of Morphology Change (RAM)
- Barrier overwash and breaching, jetty flanking
- Implicit solution - fast!
- Telescoping grids
- CMS3D - 3D flow, sediment transport, morphology change, and salinity transport

Hindered settling 'fluff layer'