CSHORE-VEG MODEL DEVELOPMENT & V&V

Liz Holzenthal (CHL-CEB), Yan Ding (CHL-CPB), Clara Zwolanek (ORISE), Nat Harris (ORISE), Emily Russ (EL), Brad Johnson (CHL-CPB)

District PDT: Kelly Legault (RSM TCX), Laurel Reichold (RSM TCX), Matthew Schrader (SAJ)

1 October 2024

COASTAL INLETS RESEARCH PROGRAM

FY24 IN PROGRESS REVIEW

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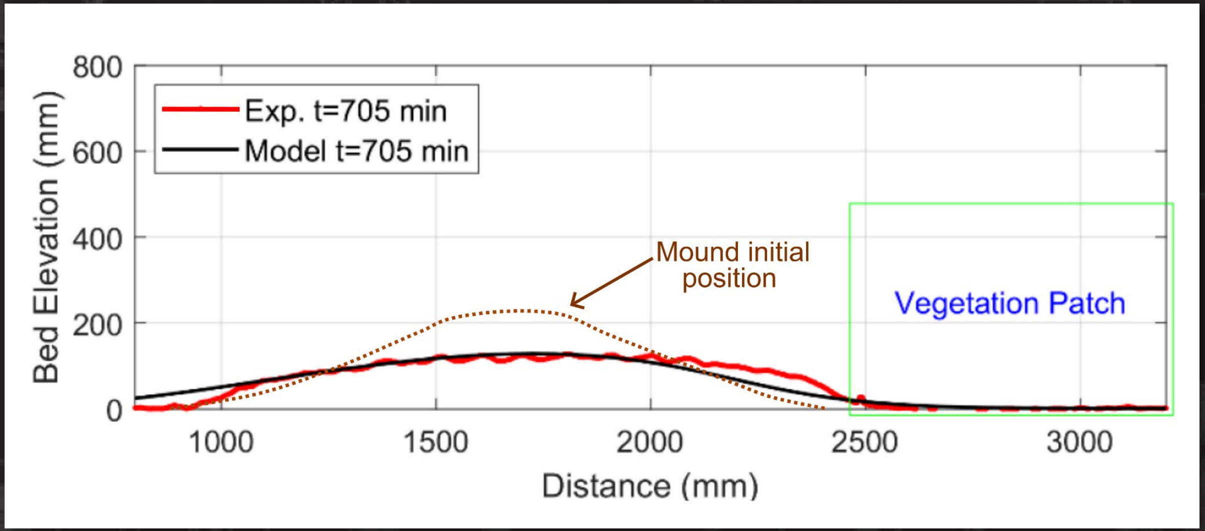

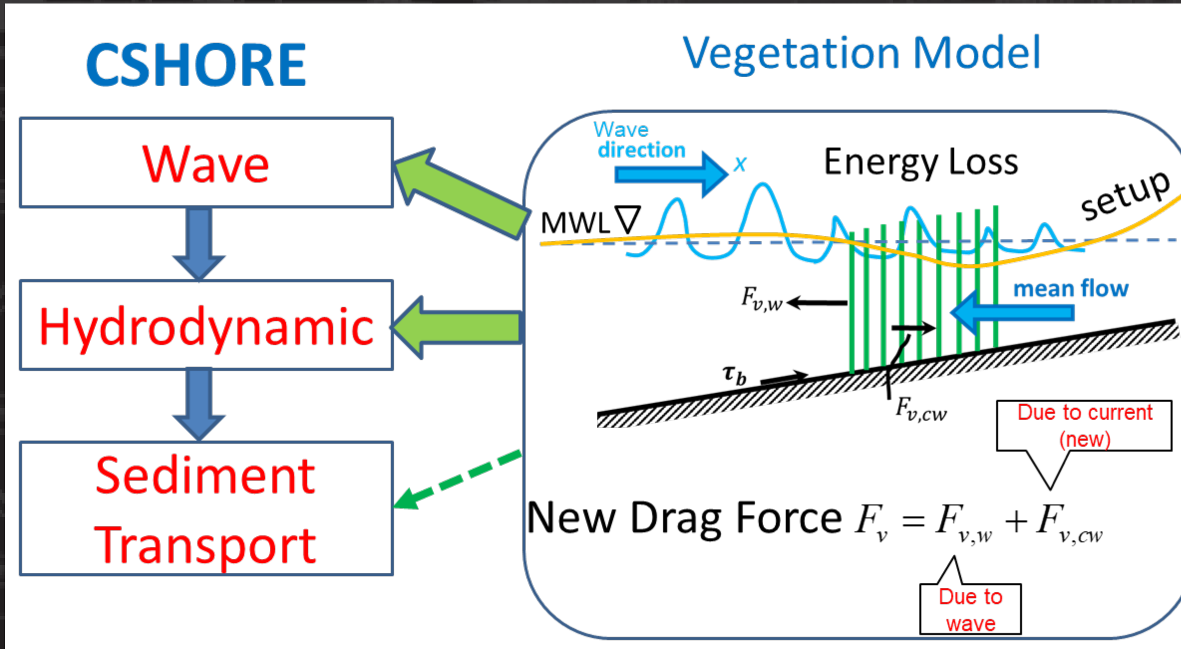

PROBLEM STATEMENT

Desire for NNBFs/NBS is great, requires understanding long-term hydrogeomorphic impacts of BUDM placement in coastal wetlands and estuaries. To address these uncertainties, a high-fidelity spatially explicit model that captures interaction of wave, flow, sediment, and vegetation dynamics is required .

Although CHL Model Modernization efforts have advanced the state of flooding prediction by hydraulic and hydrologic models, ***USACE is currently lacking in complementary advancement in sediment transport and geomorphology models that can help Districts identify opportunities for BUDM, particularly in vegetated environments***.

Statement of Needs:

2024-N-1970: “Multi-scale analyses of BUDM impacts on long-term navigation channel maintenance”

2024-N-1921: “Investigation of how BUDM can help augment, restore, or create eelgrass habitat in estuaries along the Pacific Coast”

FY24 was Year 1 of 3 (6 mo. delay)

2 Team members added (ORISE)

1 Storyboard

1 PDT meeting

CAPABILITY AND STRATEGIC IMPACT

CSHORE-Veg development continues the arc of CMS-CSHORE advancement by:

1. Expanding the toolbox of models used by Districts to predict regional-scale sediment transport
2. Beginning a framework to facilitate inter-model compatibility across hydro-geomorphic and ecological models

Improved sediment transport models ***reduce uncertainty associated with in-water placements***, potentially increasing BUDM locally as opposed to offshore placement. Geospatial model products can be visualized to ***help demonstrate to stakeholders the value*** of BUDM placement in vegetated areas.

Example applications of CSHORE-Veg model include:

- Timing BUDM to coincide with optimal vegetation habitat characteristics, which may evolve considerably over inter-annual and seasonal cycles
- Quantifying short- and long-term environmental benefits of coastal wetland/marsh restoration for erosion reduction of shoreline and marsh edge, as well as flood risk reduction
- BUDM cited sited near existing SAV habitat that may either act as a sediment sink or source depending on modeled hydro- and sediment dynamics

ENHANCING + INTEGRATING EXISTING MODEL ADVANCEMENTS

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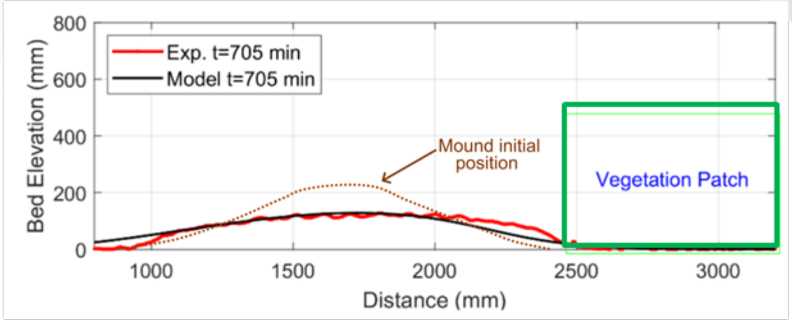
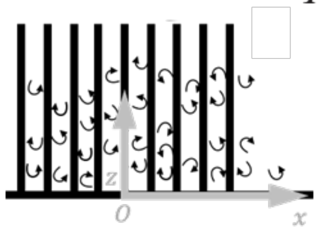
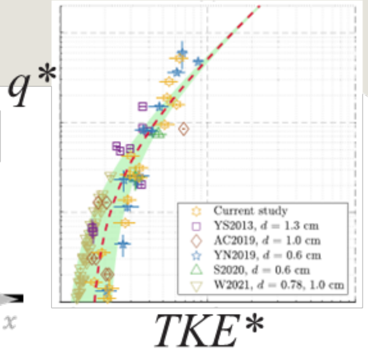
CSHORE-Veg (Y. Ding)

Sediment transport around/near vegetation

Stem-scale turbulence is the driver of between-stem transport





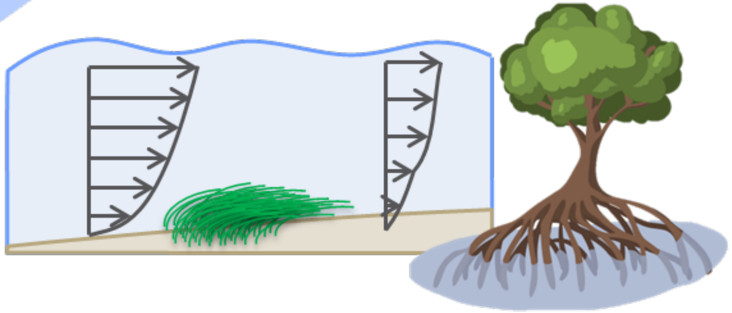


CMS-Veg

CSHORE (B. Johnson)

Wave attenuation and impact on momentum balance

Drag-related characteristics can very over depth (and with time)

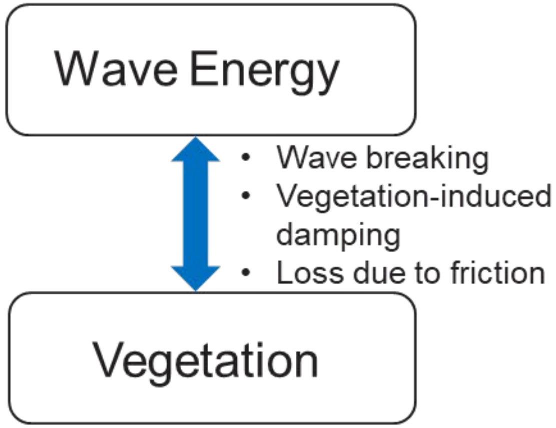


**Without properly accounting for unique vegetation characteristics and their influence on waves, current, & sediment transport, we risk over/underpredicting their engineering services (FRM & Nav)*

CSHORE WAVE MODEL WITH VEGETATION EFFECT

Phase-Averaged Wave Energy in Cross-Shore Direction (Chen et al. 2022; Johnson et al. 2012)

$$\frac{\partial}{\partial x}\left[\frac{E}{\omega}\left(C_g + \frac{Q_x}{h}\right)\right] = \frac{D_B + D_f + D_v}{\omega},$$



E = Specific wave energy

ω = Intrinsic angular frequency

Q_x = Cross-shore volume flux

D_v= Energy Dissipation due to vegetation resistance (Mendez and Losada 2004,Zhao and Chen 2012)

D_B= Energy loss due to wave breaking (Battjes and Stive 1985)

$$D_B = \frac{\rho g a_s Q H_B^2}{4T}$$

Q = Fraction of breaking wave: $\frac{Q-1}{\ln Q} = \left(\frac{H_{rms}}{H_m}\right)^2$

H_m = local depth-limited wave height $H_m = \frac{0.88}{k}\tanh\left(\frac{\gamma kh}{0.88}\right)$

a_s=slope effect parameter: $a_s = \frac{2\pi S_b}{3kh} \geq 1$

D_f= Energy loss due to bottom friction

TWO ENERGY DISSIPATION MODELS IN CSHORE-VEG

The energy dissipation rate (D_v) due to vegetation is calculated using the formulas proposed by:

1. *Bulk Dissipation:* Mendez and Losada (2004): Good for emergent vegetation and $k_p h < 1$, storm conditions

$$D_v = \frac{1}{2\sqrt{\pi}} \rho C_D b_v N_v \left(\frac{kg}{2\omega}\right)^3 \frac{\sinh^3(kh_v) + 3\sinh(kh_v)}{3k\cosh^3(kh)} H_{rms}^3$$

b_v = the plant area per unit height of each vegetation stand normal to horizontal velocity (m)
N_v = number of vegetation stands per unit horizontal area (m^{-2})
C_D = depth-averaged drag coefficient

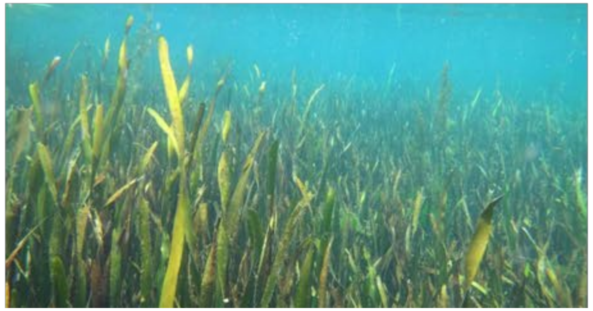
* Currently assumes vegetation blade/stem morphology

2. *Frequency-Distributed Dissipation:* Chen and Zhao (2012): Good for submerged vegetation (Jacobsen 2019)

$$D_v = \int S_{ds}(\omega) d\omega$$

with $S_{ds}(\omega) = -\frac{1}{2}\frac{C_D b_v N}{g}\frac{\omega^2}{\sinh^2 kh}\left\{\int_{-h}^{-h+h_v} U_{rms}(z)\cosh^2[k(h+z)]dz\right\}E(\omega)$

$$U_{rms}(z) = \sqrt{2\int \frac{\omega^2 \cosh^2 k(h+z)}{\sinh^2 kh} E(\omega) d\omega}$$



CSHORE-VEG WITH VEGETATION EFFECT - FLOW MODEL

Phase- and Depth-Averaged Momentum equation in Cross-Shore Direction Including Wave Nonlinearity (Chen et al. 2022, Zhu et al. 2023, Johnson et al. 2012)

$$\rho g h \frac{\partial \eta}{\partial x} = -\frac{\partial}{\partial x}\left[S_{xx} + \rho \frac{Q_x^2}{h}\right] + \tau_{sx} - \tau_{bx} - f_{v,w} - f_{v,m}$$

S_{xx} = Cross-shore radiation stress (roller effect included)

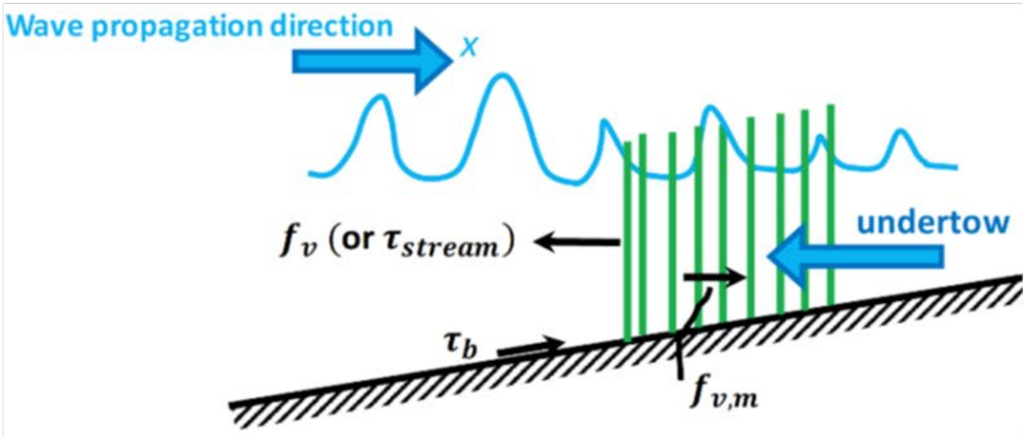
$f_{v,w}$ = drag force on water column by vegetation stem due to waves (Morison et al. 1950)

$$f_{v,w} = \frac{1}{T}\int_t^{t+T}\int_{-h_0}^{\eta} \frac{1}{2}\rho C_D b_v N_v |u_w| u_w \, dz\, dt$$

$f_{v,m}$ =drag force of vegetation against mean current (e.g. undertow) (Zhu et al. 2018)

Model features for irregular waves:

- Steady State of mean flow
- Drag forcing of vegetation from linear wave theory
- $f_{v,m}$ = 0 for Linear Wave, ≠0 for nonlinear waves
- Unidirectional wave direction



CSHORE-VEG MODEL OF FLEXIBLE VEGETATION

- Flexible Vegetation Model

For stem and blades, a scaling law (Lei and Nepf, 2019) is used to determine the effective length $h_{b,e}$

$$h_{b,e} = 0.94 h_b (CaL)^{-1/4}$$

Cauchy Number: $Ca = {\rho b U_w^2 h_b^3}/{EI}$

Length Ratio: $L = {2\pi h_b}/{U_w T}$

Effective Total Height (ETH) = Effective Stem Height (EST) + Effective Blades Height (EBH) :

$$h_{vt,e} = h_{stem,e} + \sum_i^n h_{blade,i,e}$$

- Wave Energy Dissipation for flexible vegetation

$$D_v = \frac{1}{2\sqrt{\pi}} \rho C_D b_v N_v \left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3(kh_v) + 3\sinh(kh_v)}{3k\cosh^3(kh)} H_{rms}^3$$

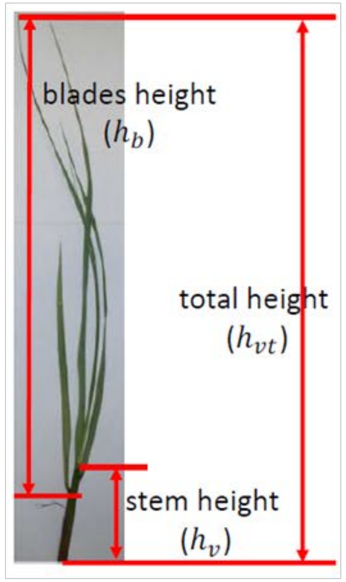
Effective total height

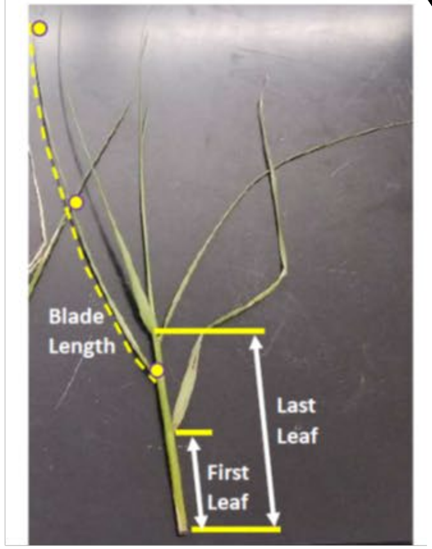
- Drag force using SFWT

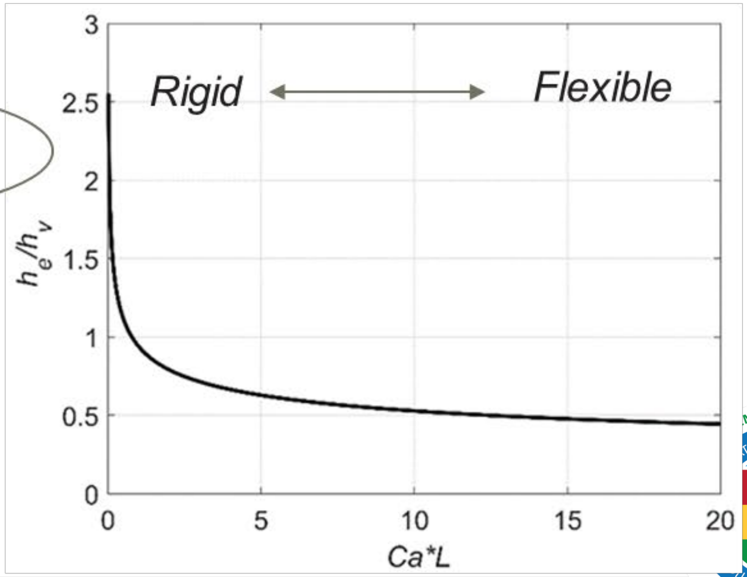
$$F_v = \frac{1}{16\sqrt{\pi}} \rho C_D b_v N_v \varpi^2 H_{rms}^3 \frac{\cosh^2 \bar{k}h_v}{\sinh^2 \bar{k}h_v} f_\alpha$$

Need C_D

C_D=drag coefficient for marshes for both D_v and F_v







JUPYTER NOTEBOOK: OPEN-SOURCE WEB APPLICATION

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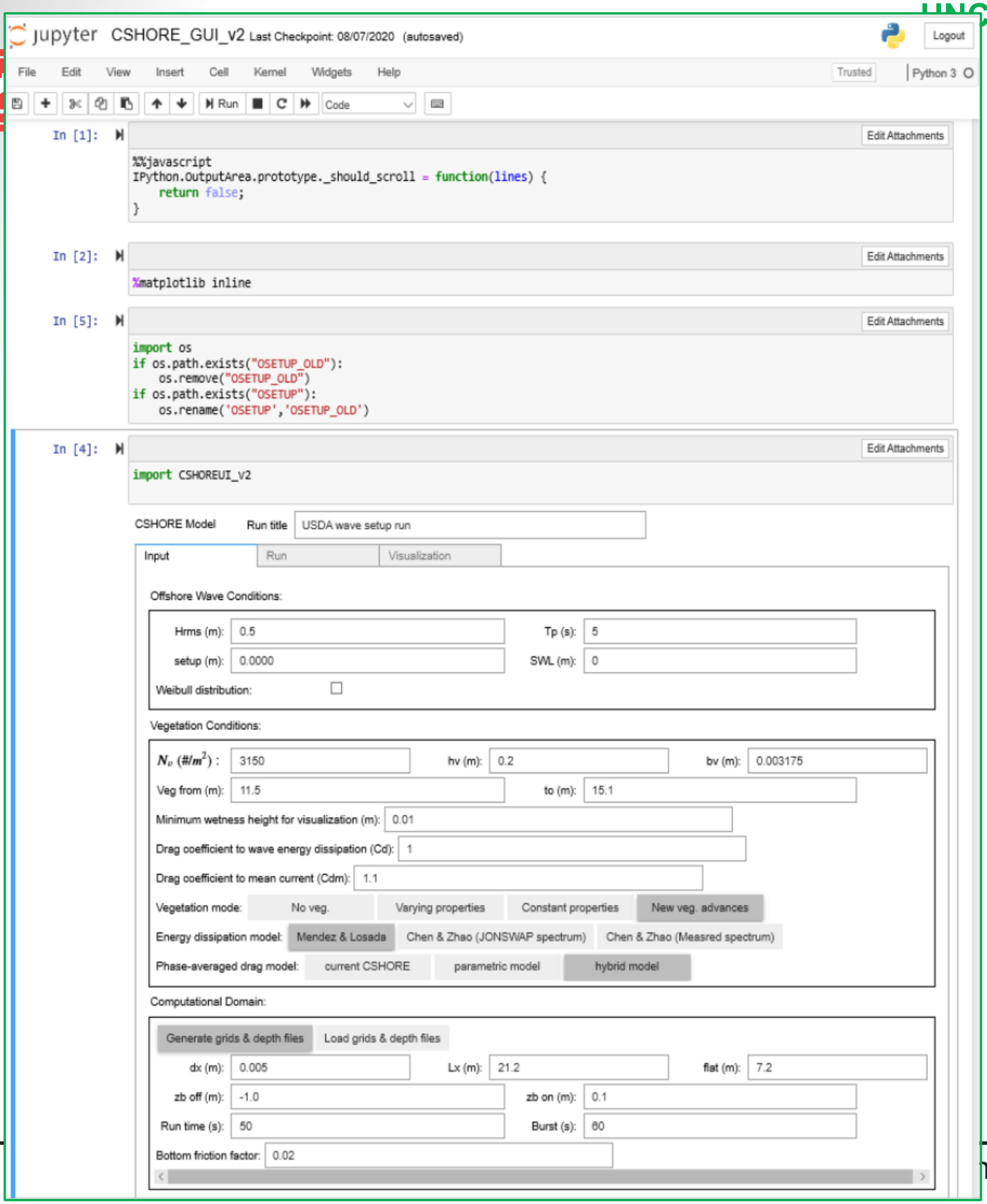


CSHORE GUI: Python; CSHORE-Vegetation: Fortran; Platform: Win/MacOS/Linux

jupyter CSHORE_GUI

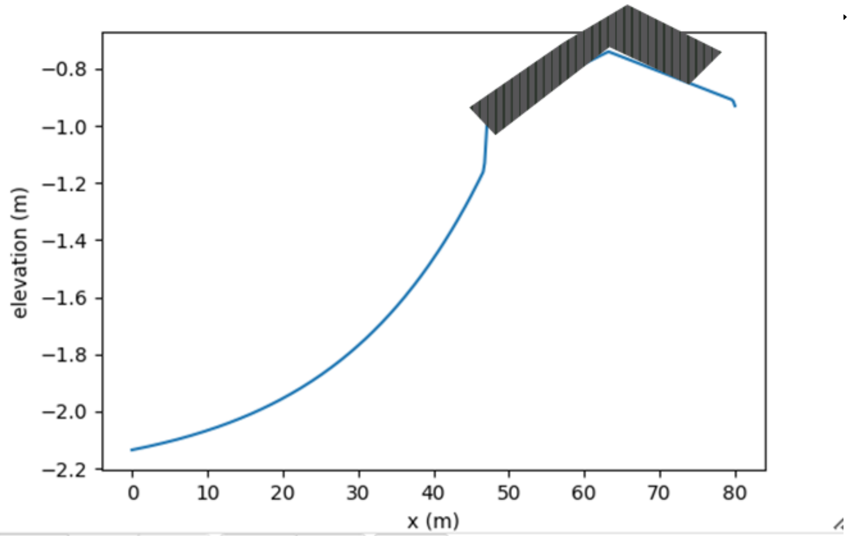
- The front-end, Web-based user interface (UI) : (1) *INPUT*, (2) *RUN*, (3) *OUTPUT VISUALIZATION*, and (4) *BREAKAGE EVALUTION* ; built upon Jupyter notebooks, streamlines the workflow of model configuration, execution, and output visualization

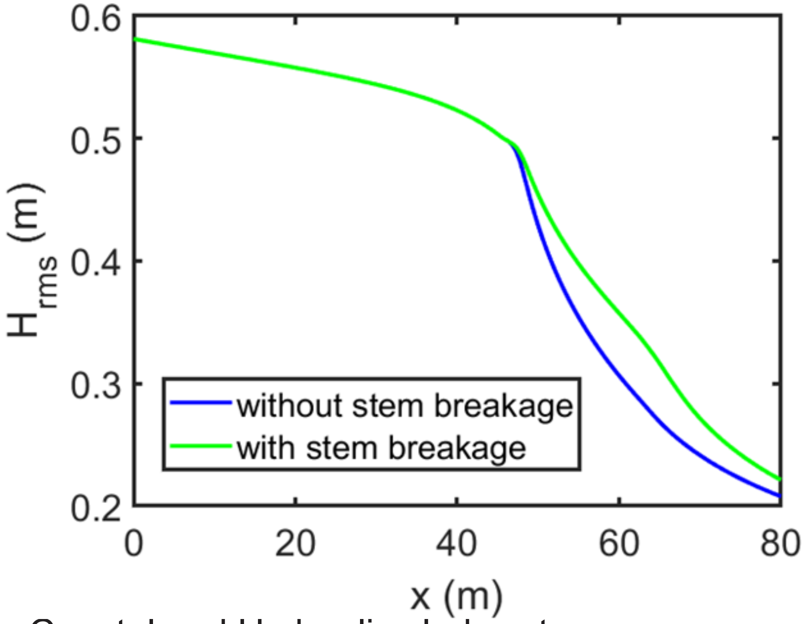
- The back-end vegetation breakage evaluation engine conducts Monte-Carlo simulations, computes wave-induced bending stress through a trained neural network model, determines vegetation breakage fractions, and simulates wave height decay in response to the remaining vegetation stems using CSHORE-VEG.

Zhu et al. (2022) ERDC/CHL CHETN-IV-DRAFT

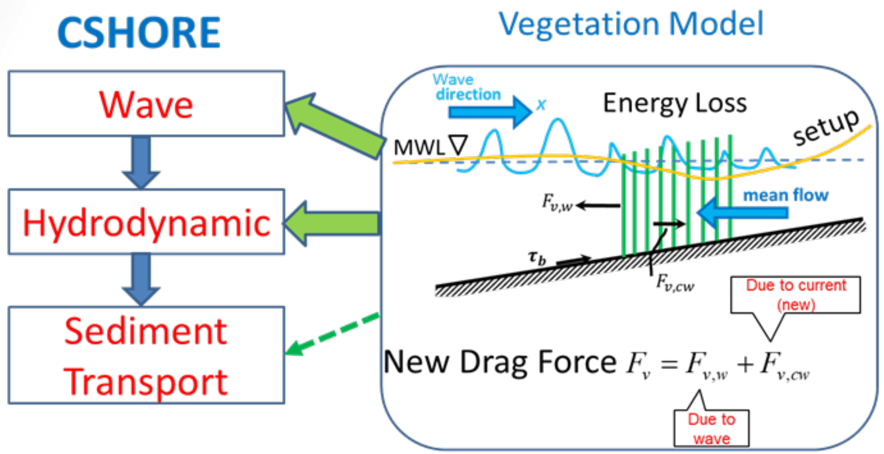
EXAMPLE CASE: TERREBONNE BAY WAVES FROM TS LEE (2011)

```
Wave boundary conditions:
Hrms0:  0.5813 m
Tp: 3.1850 s
angle: 0 deg
mwl: 0 m
swl: 0 m

Process:
breaking ratio: 0.90

Vegetation:
extent: from 47.0000 m  to  79.7000 m

flexible vegetation

stem breakage
Nv: 400 stems/m2
mean hstem: 0.1578 m
std hstem: 0.1436 m
mean bv: 0.0079 m
std bv: 0.0028 m
mean flexural strength: 6000000 Pa
std flexural strength: 4600000 Pa
Young's E: 80000000 Pa

Cd should be 0.8323
```





INTERACTION BETWEEN SEDIMENT TRANSPORT AND VEGETATION: A GENERAL FRAMEWORK



Bed Elevation Change (Z_b) Model

$$(1-p)\frac{\partial Z_b}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

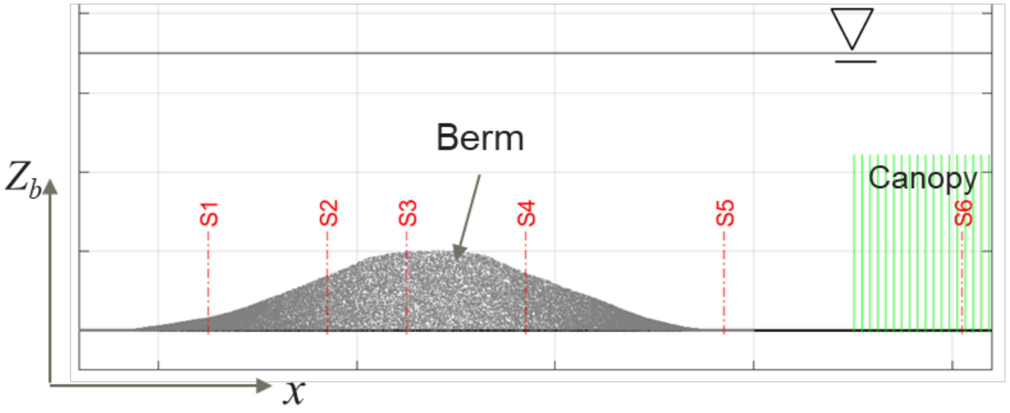
Q = sediment transport flux induced by waves and currents

P = sand porosity

Q: Need a Cross-Shore Sediment Transport through Vegetation

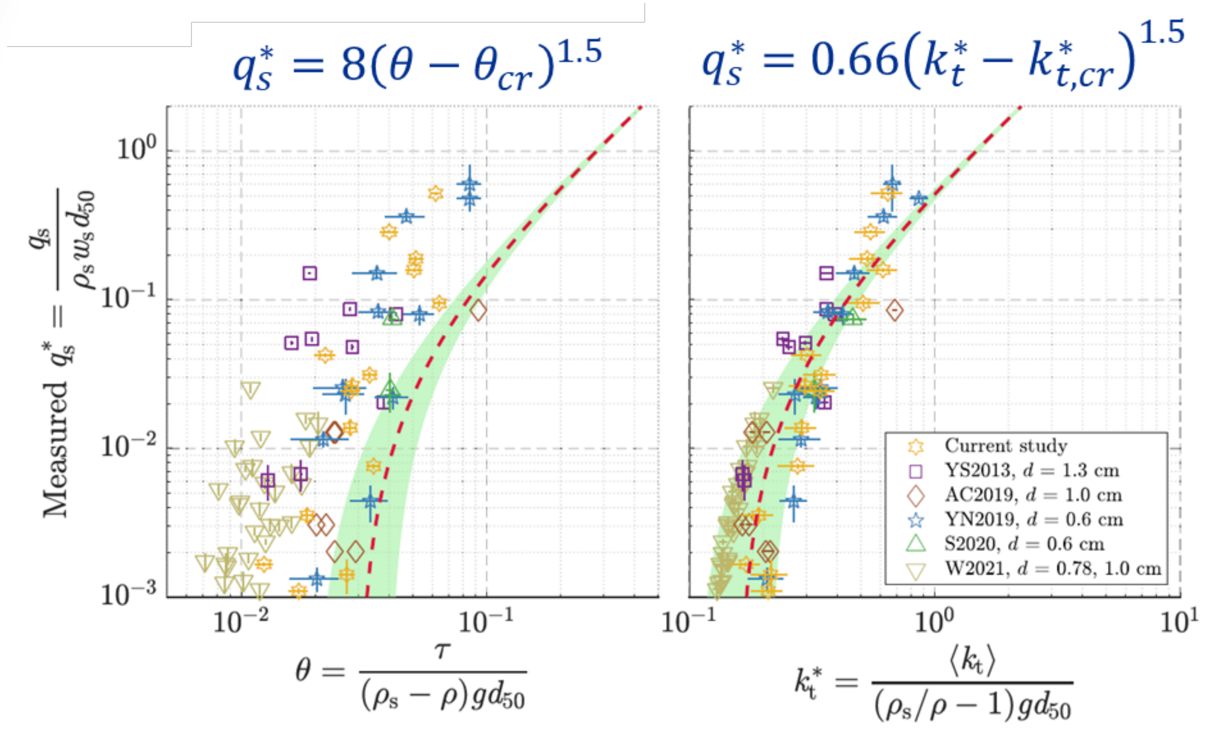
Contributors to Cross-Shore Transport:

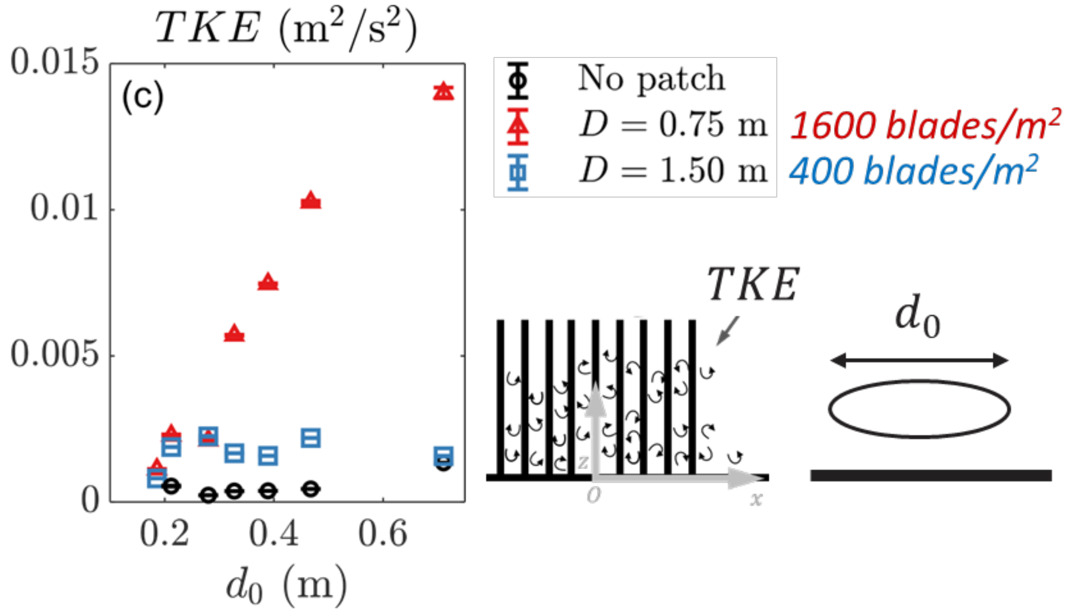
- Orbital motion of nonlinear waves (on-offshore)
- Undertow in 3-d current structure by waves (offshore)
- Gravitational slope effect (offshore)
- Stokes drift: a net drift velocity in the direction of wave propagation.
- Overwash and overtopping (not included in the present model)
- Sandy bar migration (at on-offshore directions)
- Turbulence induced by vegetation
- Suspension and bed materials in vegetation due to waves and currents



TURBULENT KINETIC ENERGY (TKE) & VEGETATION

- Growing body of literature based on laboratory and field studies support TKE as a better predictor of sediment transport in vegetation canopies than bed shear stress
- Zhao and Nepf (2021) recast MPM bedload transport equation as $f(TKE)$ instead of $f(\theta)$
- TKE generally increases with stem packing density and velocity (e.g., Holzenthal et al. 2022)





NON-UNIFORM VEGETATION GEOMETRY

Mangrove flume experiment validated in CSHORE (Johnson FY24); drag prediction simplified to focus on momentum balance and veg impact on mean water level

- Energy

$$\frac{\partial \overline{E_f}}{\partial x} = -D_B - D_f - \overline{\int_{zb}^{\eta} \rho \frac{C_D}{2} d_v N |u|^3 dz}$$

- Momentum

$$\frac{\partial S_{xx}}{\partial x} = -\rho g h \frac{\partial \overline{\eta}}{\partial x} - \tau_b - \overline{\int_{zb}^{\eta} \rho \frac{C_D}{2} d_v N |u| u dz}$$

d_v = plant diameter/width [m]
N_v = number of stems/plants per unit area (m^{-2})
C_D = drag coefficient

$$\rho \frac{C_D}{2} b_v N |u| u = \beta |u| u$$

$$\beta(z) \sim \rho \frac{C_d}{2} D_e(z) n_R(z)$$

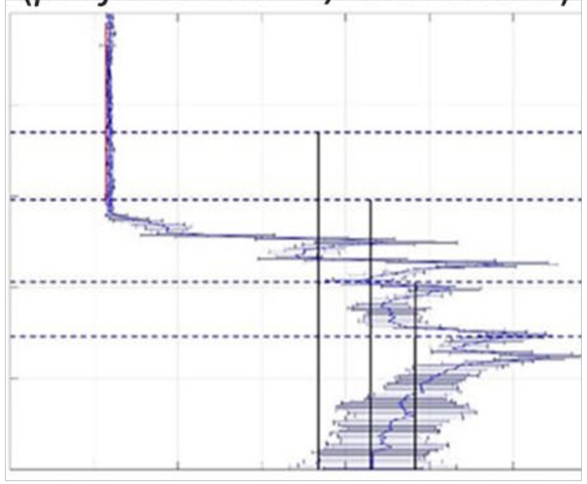
Kelty et al. (2022)

$D_e(z) \sim b_v \sim d_v$

$$D_e = \frac{\overline{A_t}}{(1 + \overline{n_R})}$$

D_e = effective diam.
n_r = num. roots

A_t [m²/m] (*projected area / unit width*)



SUMMARY

FY24 Major Advancements in Capability

- 2 Contracts managed/awarded (ORISE)
- New team members (ORISE) to perform V&V of model advancements made by team leads
- Preliminary literature review and plan for formulation additions/enhancements

FY24 Major Products & Collaborations

- PDT meeting
- Periodic meeting with EL GenVeg team members
- TN on CSHORE-Veg GUI submitted into EPAS**

FY25 Products & Advancements

- 1D validation of hydro, vegetation, sediment formulations with TKE-induced transport
- 1D validation of wave, vegetation, and drag formulations for species with large depth-variation (i.e., mangroves)
- JP/TR draft on TKE-induced transport advancements in CHSORE-Veg
- JP/TR draft on drag formulations for mangroves in CHSORE-Veg
- TN draft on spatial and temporal scales of data needed by CHL and EL models; identify possible model coupling framework
- White paper on CSHORE-Veg formulations (in comparison with CSHORE and C2SHORE)