NNBF

International Guidelines on Natural and Nature-Based Features for Flood Risk Management

Mangroves

Puerto Rico I May 2022

10

Mangroves in Coastal Wetland Systems

Presenter: Tori Tomiczek, United States Naval Academy

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Jenny Davis, NOAA, Beaufort, North Carolina, United States; Trevor Meckley, NOAA, Silver Spring, Maryland, United States

Outline

- **Introduction and design considerations**
  - *International Guidelines* and mangroves within the context of coastal wetland systems
- **Motivation - why mangroves?**
  - Case study: damage observations after Hurricane Irma (2017) in the FL Keys
- **Quantifying mangrove performance metrics**
  - Reduced- and full-scale laboratory studies
  - Field-based monitoring and observations
- **Modeling capabilities**
- **Conclusions**

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Coastal Wetlands and Tidal Flats

Authors: Candice D. Piercy, Nigel Pontee, Siddarth Narayan, Jenny Davis, Trevor Meckley

Key Messages

1. Coastal wetlands and tidal flats reduce flood and erosion risks in coastal environments
2. Projects can include conserving existing wetlands, restoring degraded wetlands, or constructing new wetlands
3. Performance is controlled by location, coastline geometry, vegetation morphology, and storm characteristics
4. Wave height reduction is well documented over moderate spatial scales and depends on topography, vegetation characteristics, and storm characteristics
5. Storm surge reduction requires greater spatial scales (i.e., wetland size and extents)

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Coastal Wetlands and Tidal Flats

Authors: Candice D. Piercy, Nigel Pontee, Siddarth Narayan, Jenny Davis, Trevor Meckley

Key Messages (cont'd)

6. Coastal wetlands can provide flood storage; efficacy depends on location and design
7. Projects can draw upon extensive experience in marsh and mangrove restoration
8. Provided with the appropriate ecological and ambient wave energy conditions, coastal wetland NNBF can be self-maintaining over time.
9. Consider where wetland NNBF will persist now and under future climate and SLR scenarios
10. Performance of wetland NNBF will vary over time as vegetation establishes, develops, and recovers after disturbances

Coastal wetlands also provide numerous cobenefits (*e.g.*, habitat, Carbon sequestration)

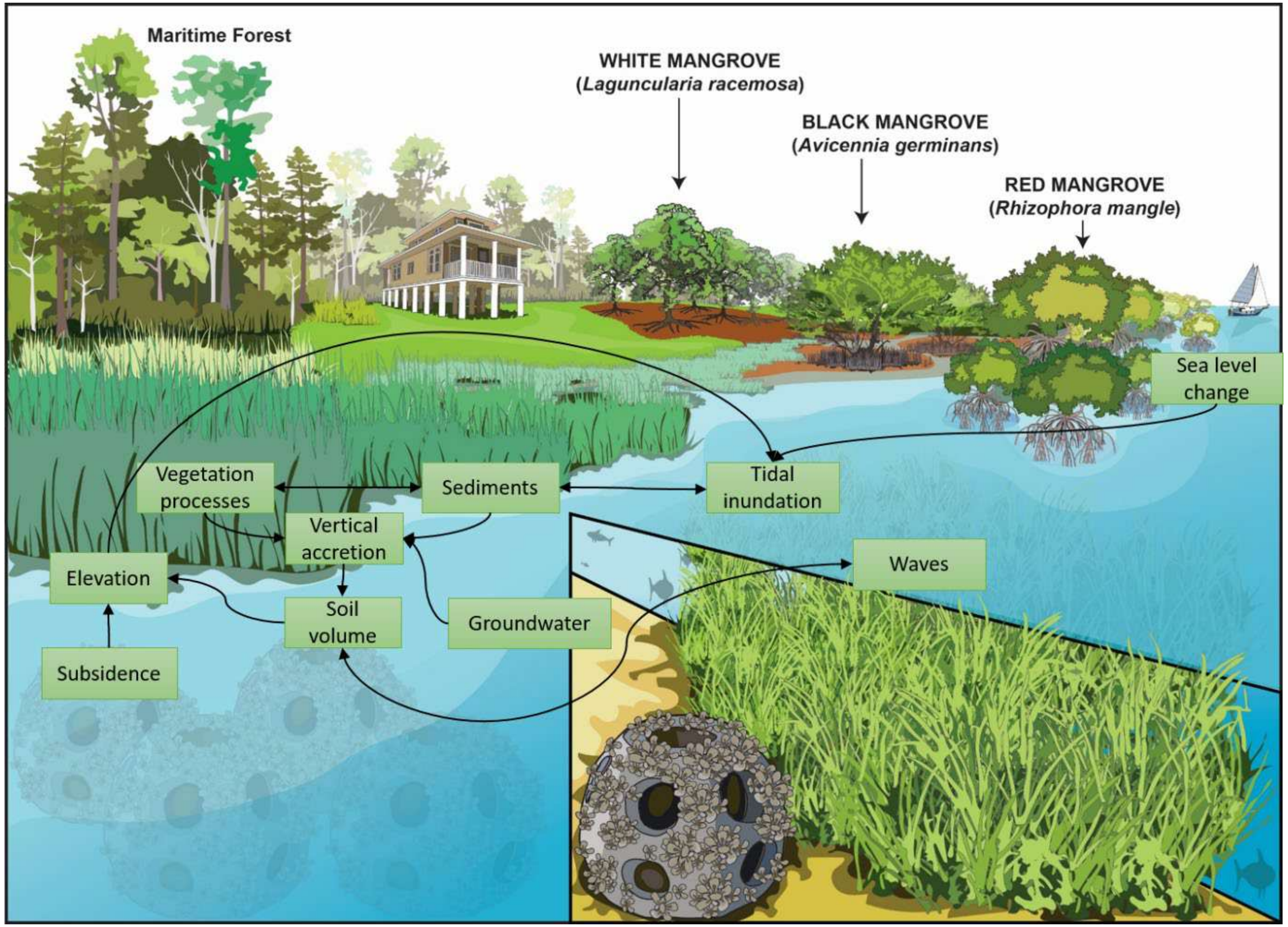
Coastal Wetland Vegetation

Flexible

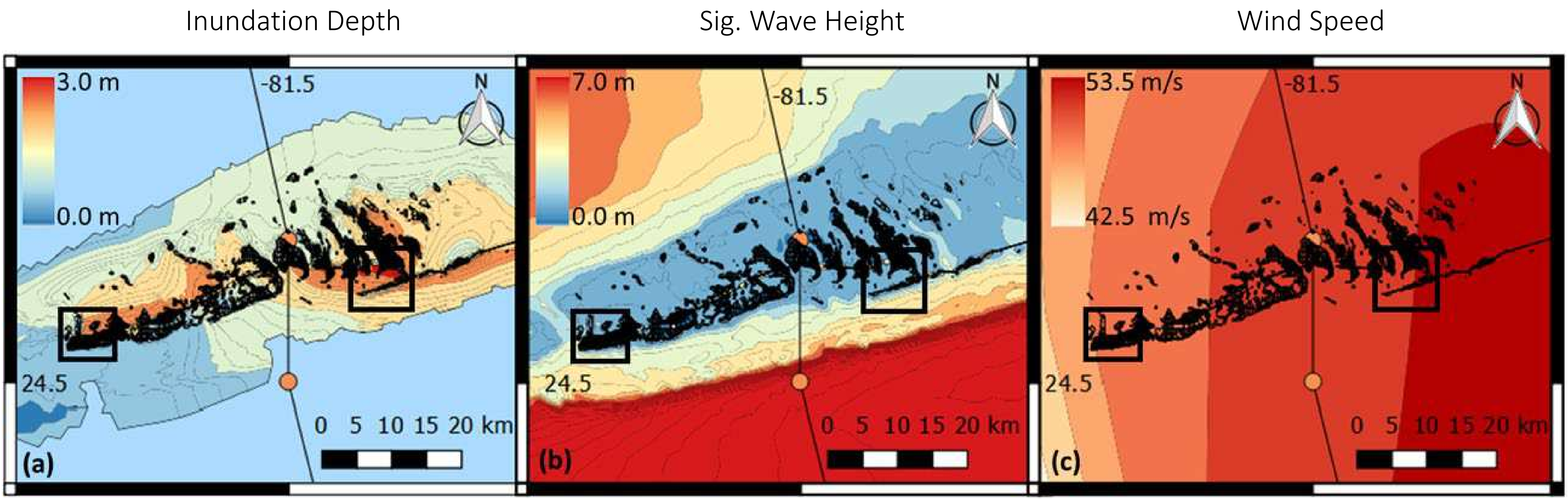
Spartina alterniflora (Smooth Cordgrass)

Rigid

Rhizophora mangle (Red Mangrove)



Motivation for Mangroves: Damage Observations after Hurricane Irma (2017) in the Florida Keys



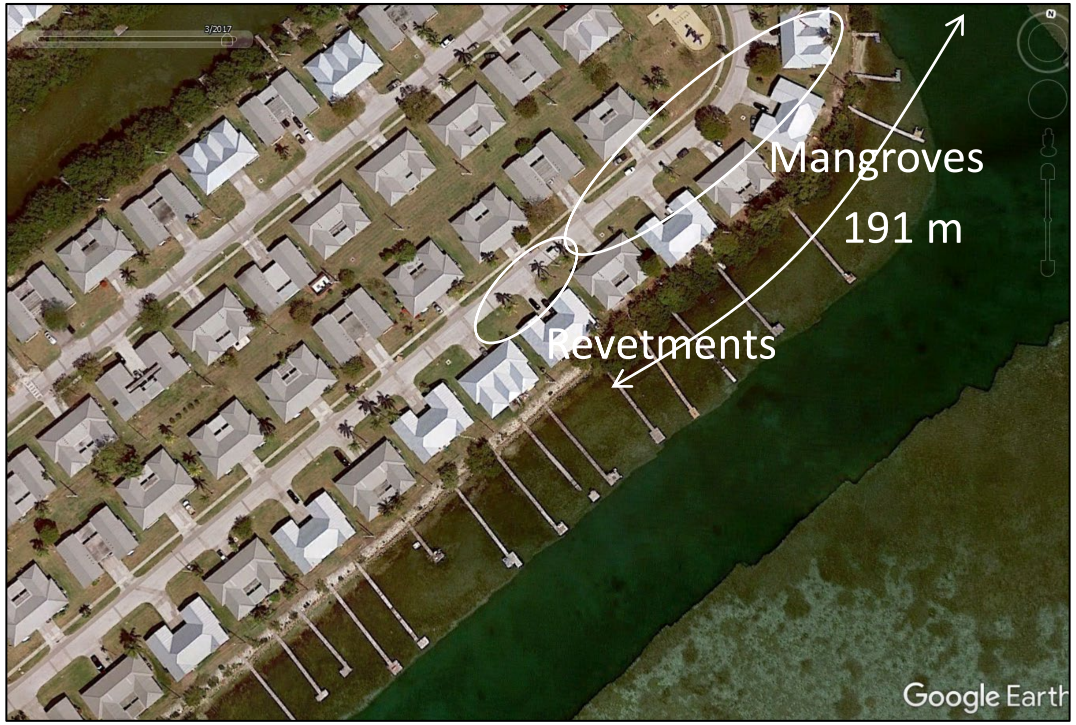
Tomiczek et al. (2020)

	Key West	Big Pine Key
Wind Velocity (m/s)	44.8-49.2	49.3-53.6
Inundation Depth (m)	1.23-2.14	1.53-2.75
Significant Wave Height (m)	0-1.83	0.92-2.74

Post-Storm Damage Assessments

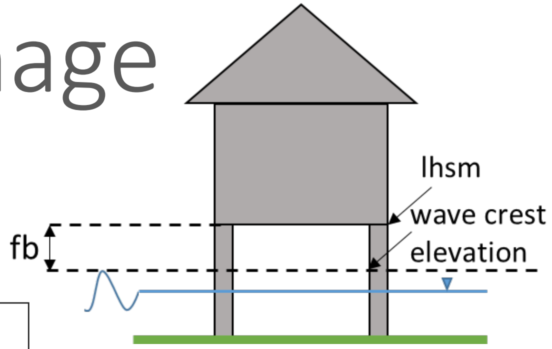
- NEU-USNA Collaborative Effort
  - July 2017- March, 2018
- Key West and Big Pine Key
- *Investigate relationship between shoreline resiliency, structural vulnerability, and shoreline management*
- **October Survey**: 263 residential structures, 332 shorelines

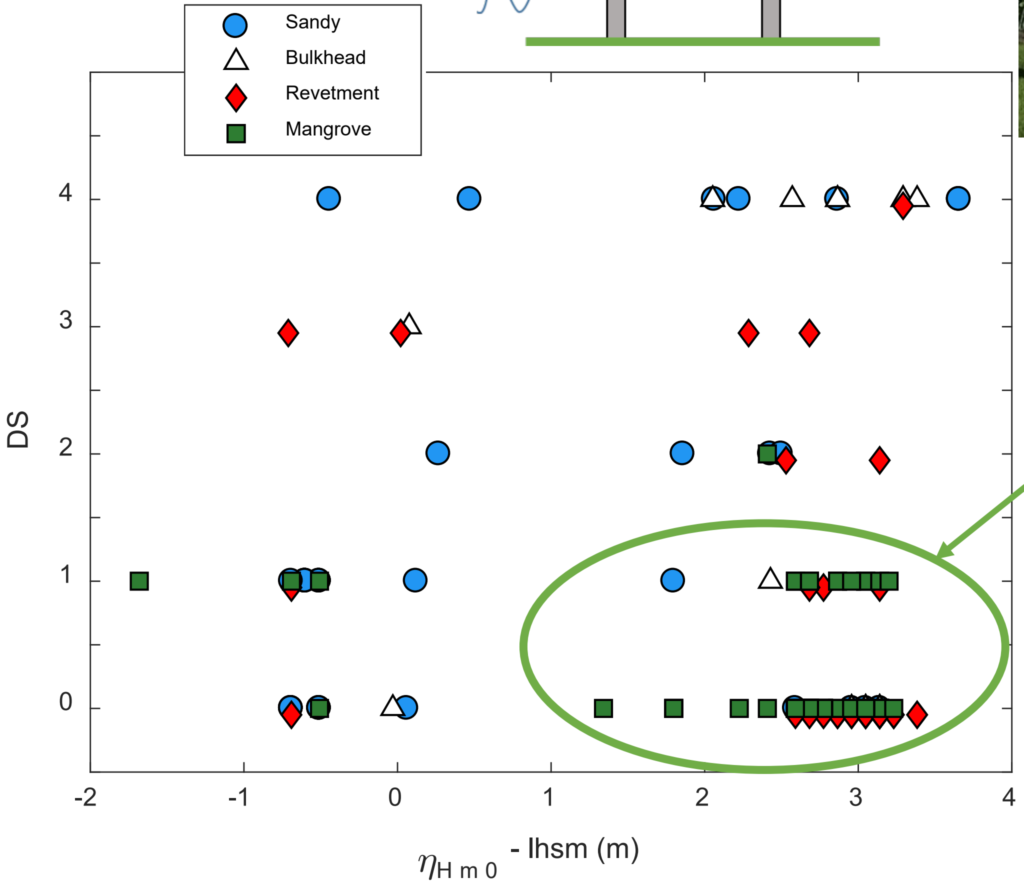
Parcel-Scale Shoreline Variability



- Shoreline archetypes based on NOAA C-CAP Classifications
- Four-point damage scale
- Mangroves show resilience

Fragility Relationships: Relate Hazard, Shoreline Type, and Damage





- Structures with mangrove shorelines: lower damage states (*DS*) for higher hazard intensities ($\eta_{Hm0} - lhsm$)
- Similar to protection noted in other studies (*e.g.* India (Danielsen et al. 2005), SW FL (Zhang et al. 2012)) for km-scale forests, but for 10-50 m cross-shore forest widths

Tomiczek, T., O'Donnell, K., Furman, K., Webbmartin, B., and Scyphers, S. (2020). Rapid Damage Assessments of Shorelines and Structures in the Florida Keys after Hurricane Irma. Nat. Haz. Rev. 21 (1) 15019006. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000349.

Need to Quantify Mangrove Performance Metrics

- **Previous Studies of wave attenuation through vegetation**
  - Anderson and Smith (2014) – *Spartina alterniflora* mimics, emergent and near-emergent
  - Ozeren et al. (2014) – idealized rigid vegetation, live wetland vegetation, emergent
  - Hu et al. (2014) – idealized rigid wetland vegetation, emergent
  - Maza et al. (2017, 2019) – *Rhizophora,* 1:12 and 1:6 geometric scales
  - Chang et al. (2019) – *Rhizophora,* 1:7 geometric scale
- **Generally quantify a drag coefficient**
  - e.g., Mendez and Losada (2004):

Ratio of transmitted to incident wave height

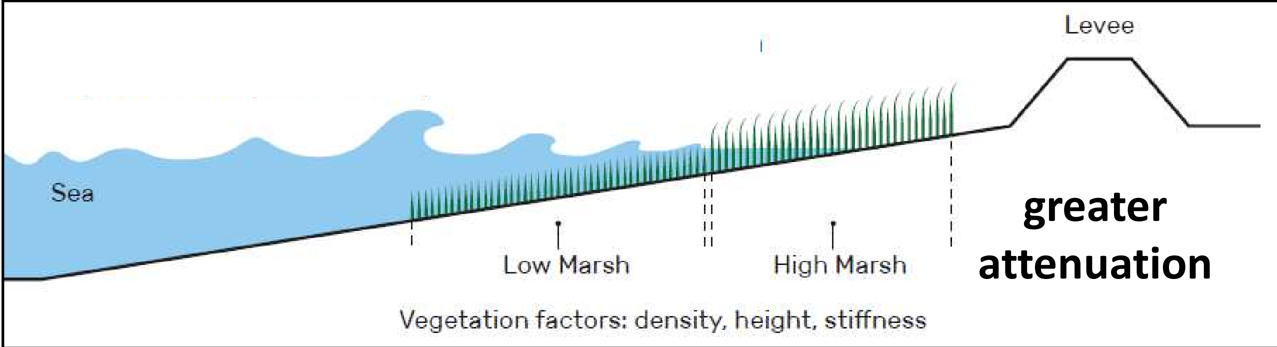
$$\frac{H_t}{H_i} = \frac{1}{1+\tilde{\alpha}x}$$

where

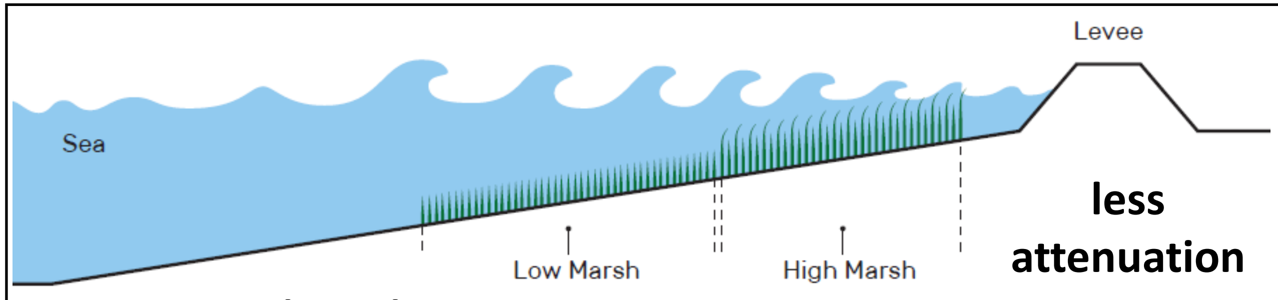
Vegetation Parameters

Hydrodynamic Parameters

$$\tilde{\alpha} = \frac{\overline{A_t} \cdot N \cdot H_{rms,i} \cdot C_D \cdot k_p}{3\sqrt{\pi}} \cdot \frac{\left(\sinh\left(k_p l_d\right)\right)^3 + 3\sinh\left(k_p l_d\right)}{\sinh\left(k_p h\right)\left[\sinh\left(2k_p h\right) + 2k_p h\right]}$$



greater attenuation



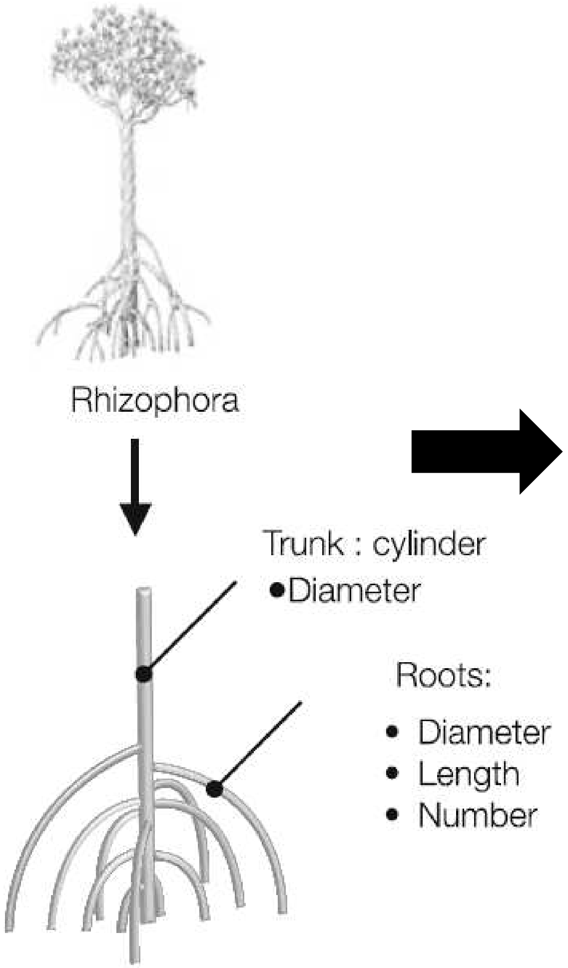
less attenuation

Piercy et al. (2021)

Reduced-Scale Physical Model of *R. mangle*

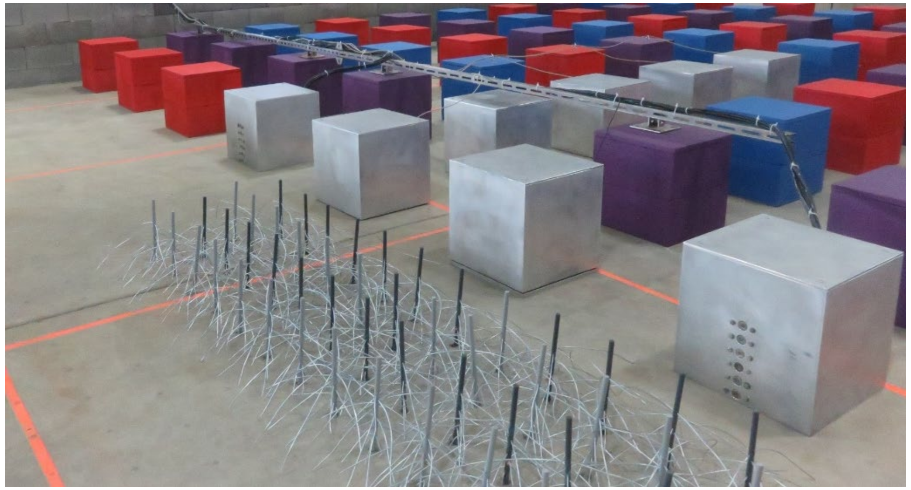
Field measurements

Parameterization



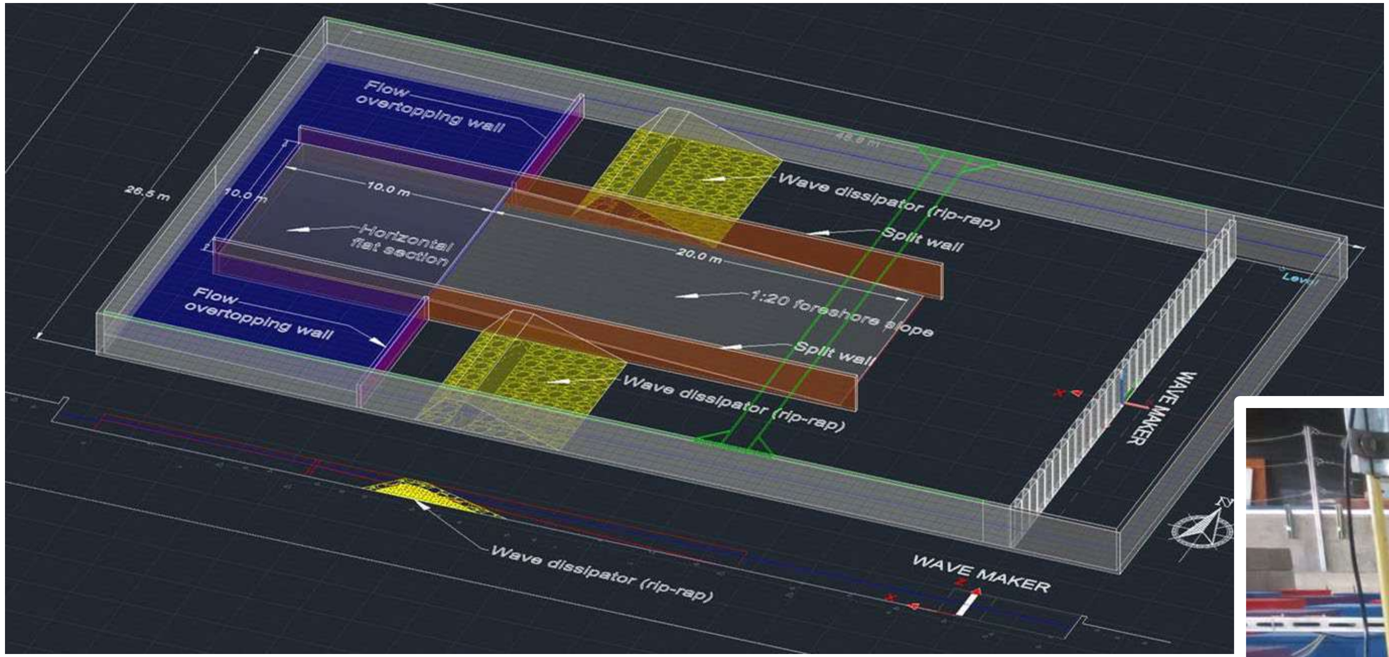
Ohira et al. (2013)

1:16 scale model

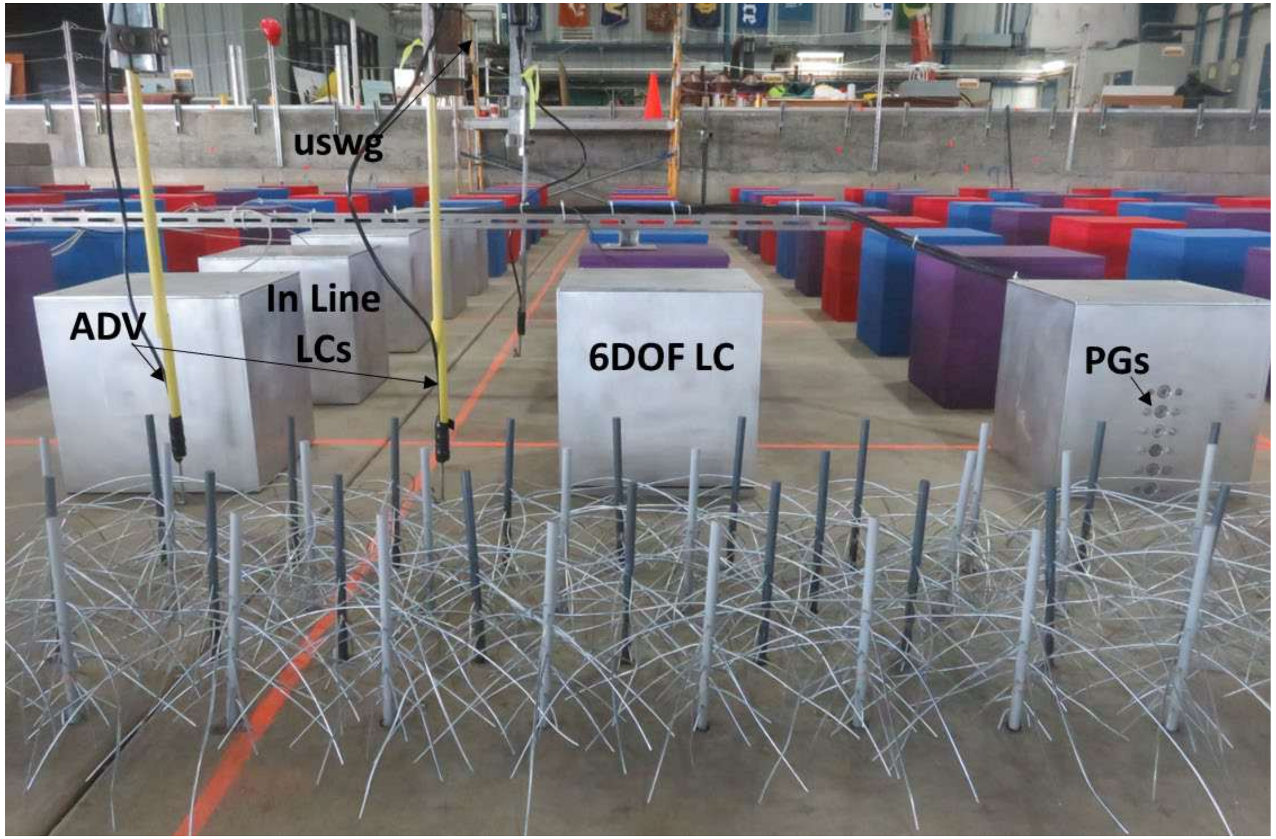


Parameter	Key West (1:1)	Model (1:16)
Material	Red mangrove	PVC + Galv. Steel
d_{trunk} (m)	0.11 – 0.28	0.013
d_{roots} (m)	0.01 – 0.06	0.0025
N_{roots}	12-24	22
h_{root}(m)	1.0 – 2.0	0.125

Overland Flow Experiments



- Larger experimental campaign by OSU, ND, USC, USNA, UH, HYU
- Novel test setup- pumps allow for waves with background current
- 1:16 geometric scale



3 experimental configurations

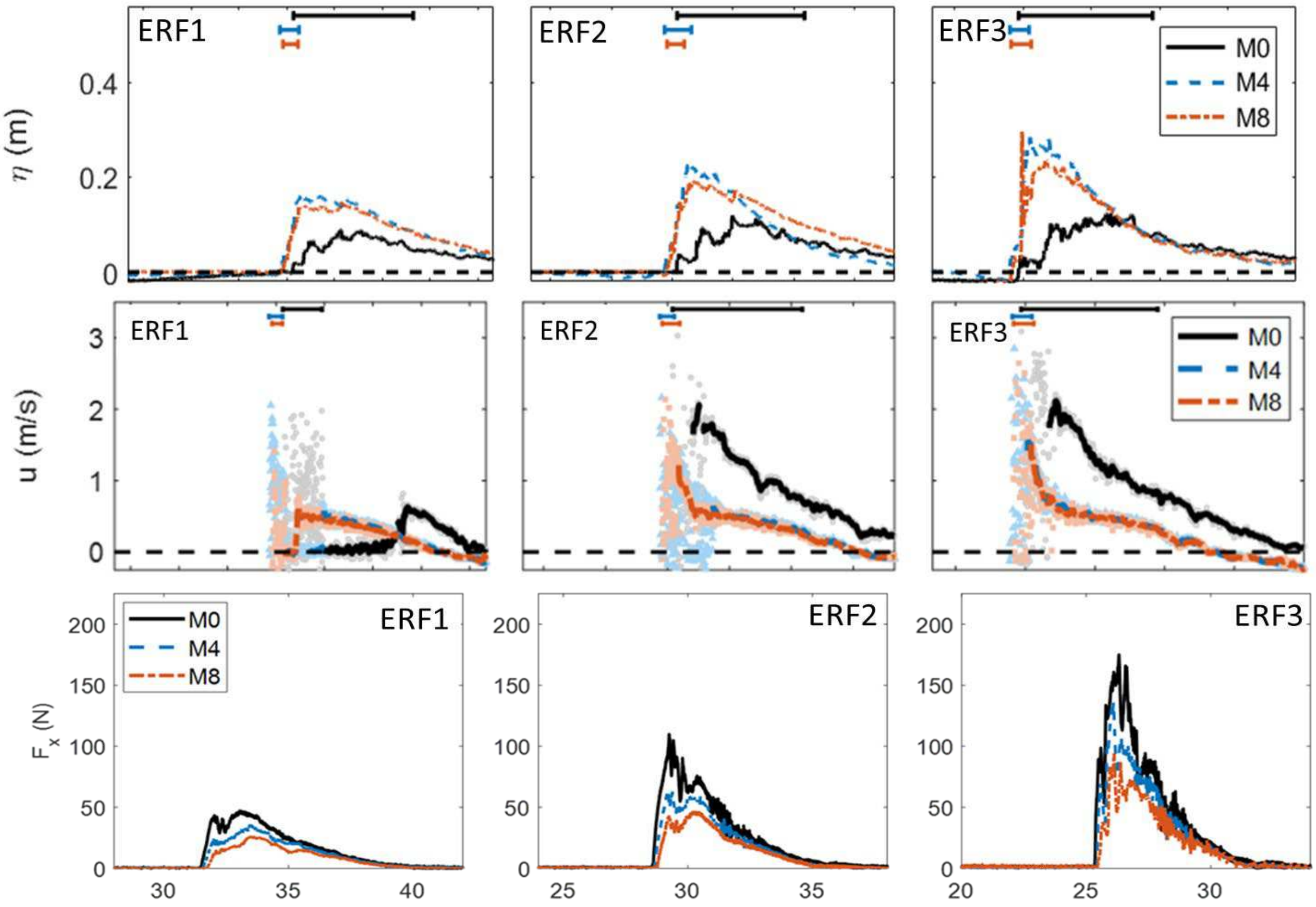
- **M0:** 0 mangroves
- **M4:** 4 rows of mangroves (50 total, 8.2 m prototype scale)
- **M8:** 8 rows of mangroves (100 total, 19.0 m prototype scale)

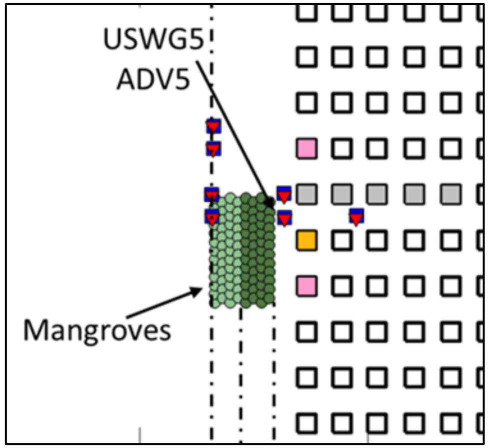
Wave Conditions

- Random (storm-like) and Transient (tsunami-like) waves
- With and without background current
- Focus on transient wave trials

Trial	$\bar{A}$ (m)	$\overline{T_R}$ (s)
ERF1	0.126	11.15
ERF2	0.144	8.30
ERF3	0.207	5.71
ERF1C	0.139	10.83
ERF2C	0.171	9.20
ERF3C	0.216	5.95
C	-	-

Mangrove Effects on Hydrodynamics and Loads



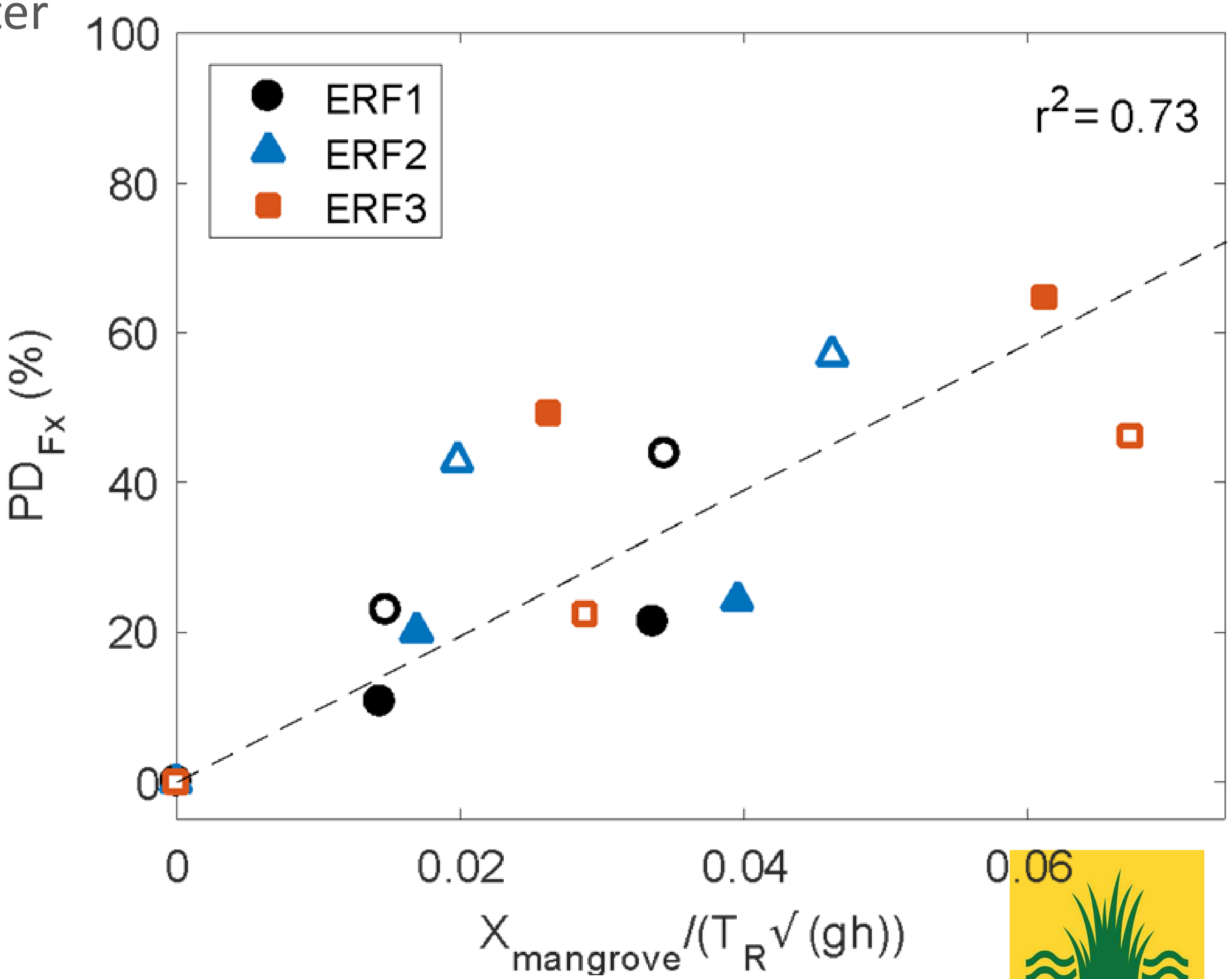


- Water levels increase behind mangroves (affected by idealized structures
- Peak velocities decrease more quickly
- Significant load reductions (not always linear)

Relationship between load-reduction, forest thickness, hydrodynamics

- Longer wave period (wavelength) → need greater cross-shore thickness for similar load reduction
- Need to validate laboratory results with field measurements, tests at other (large) scales

Trial	F_{xmax}, M0 (N)	*PD*, M0 to M4 (%)	*PD*, M0 to M8 (%)
ERF1	47.1	23	44
ERF2	110.0	43	57
ERF3	174.9	22	46
ERF1C	85.1	11	21
ERF2C	212.1	20	24
ERF3C	942.7	49	65

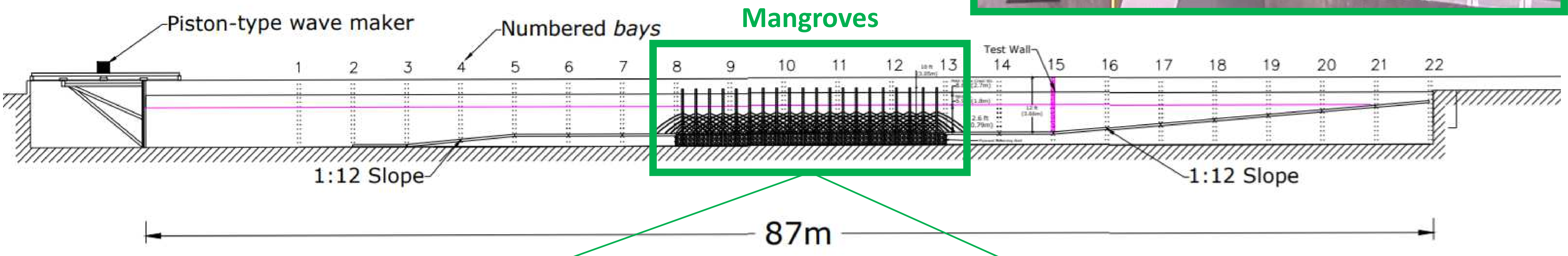


Tomiczek, T., Wargula, A., Lomonaco P., Goodwin, S., Cox, D.T., Kennedy, A.B., and Lynett, P. (2020). Physical Model Investigation of Mid-Scale Mangrove Effects on Flow Hydrodynamics and Pressures and Loads in the Built Environment. Coastal Engineering, 162 (2020). https://doi.org/10.1016/j.coastaleng.2020.103791

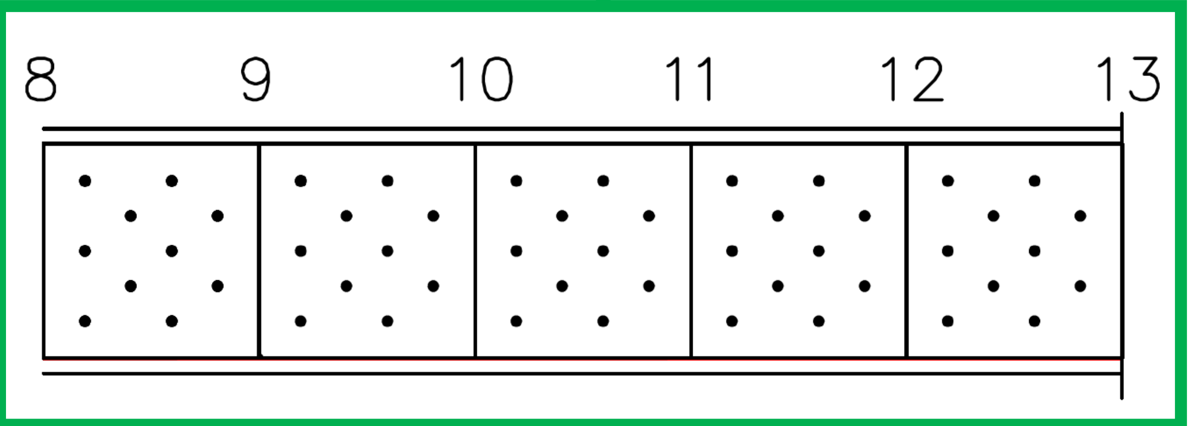
How does Hydraulic Response Change from Reduced- to Full-Scale?

- Consider scaling effects, Reynolds No.
- Collaboration with USNA, U.S. Army Corps of Engineers, Oregon State University
- Examine, compare wave attenuation (drag coefficients) by mangroves at large (1:2) and full (1:1) scale

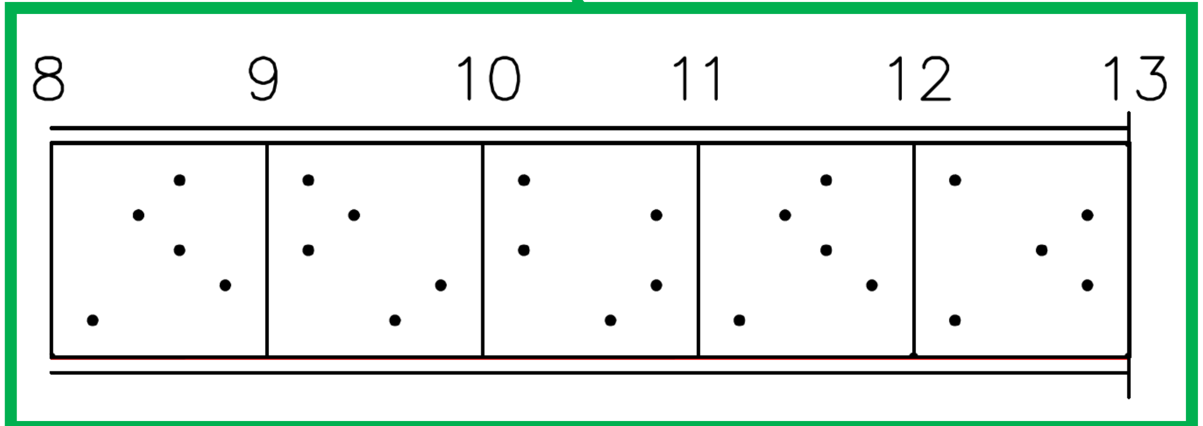
Full-Scale Physical Model of Wave Attenuation through *R. mangle*



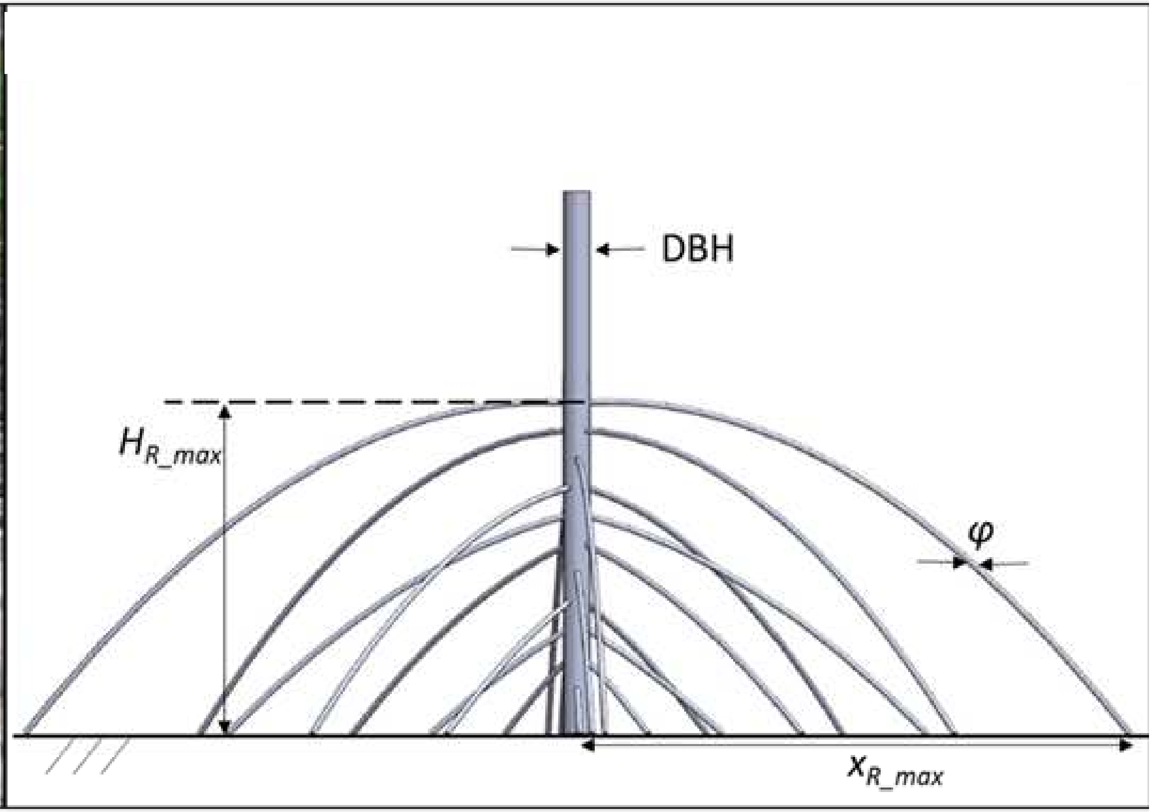
High-Density
(0.75 stems/m²)



Low-Density
(0.375 stems/m²)



Specimen Design

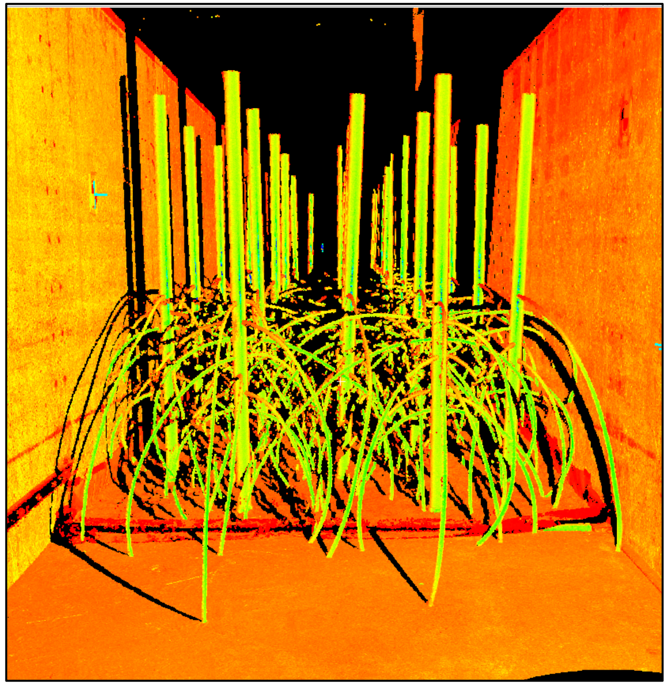


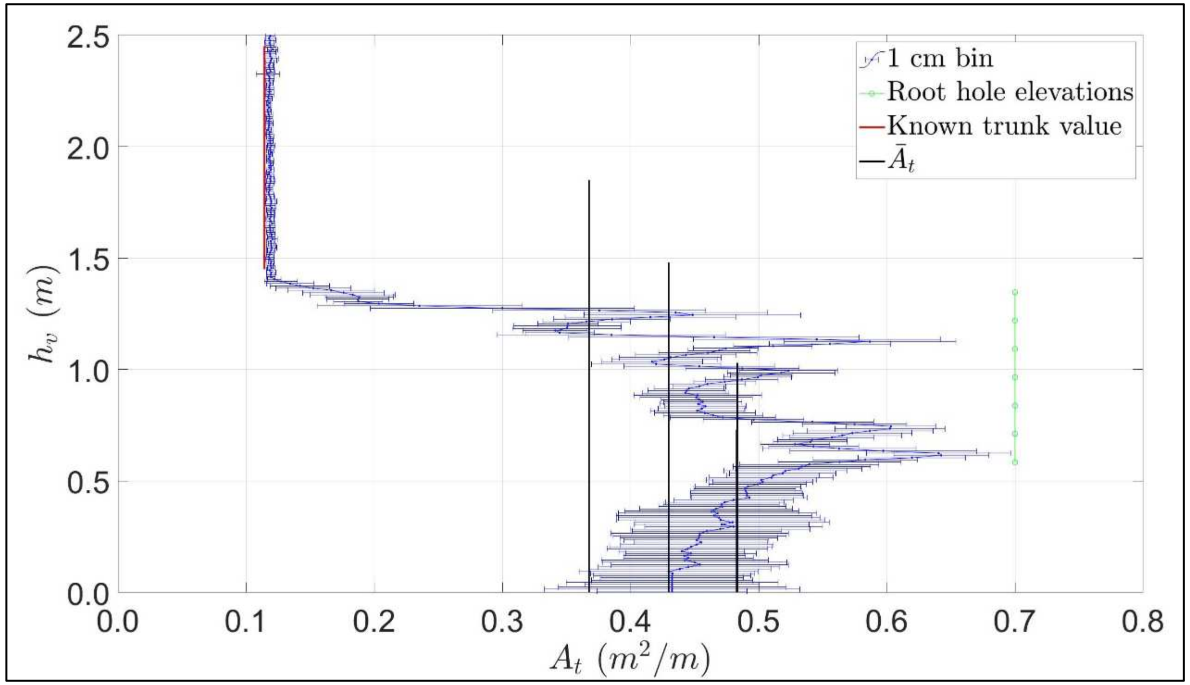
Dimension	Full Scale (m)
DBH	0.114
φ	0.029
H_{R_max}	1.445
x_{R_max}	2.58
N	14

Material	Total Length
PEX	3867 ft
PVC	625 ft

- Identical to 1:2-geometric scale specimens constructed at ERDC

LiDAR Characterizarion of Projected Area

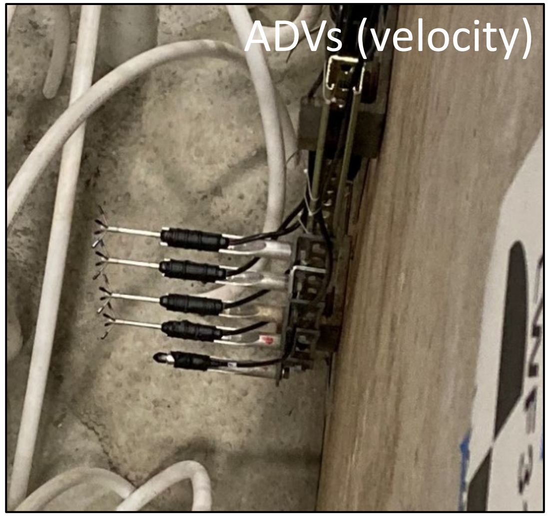


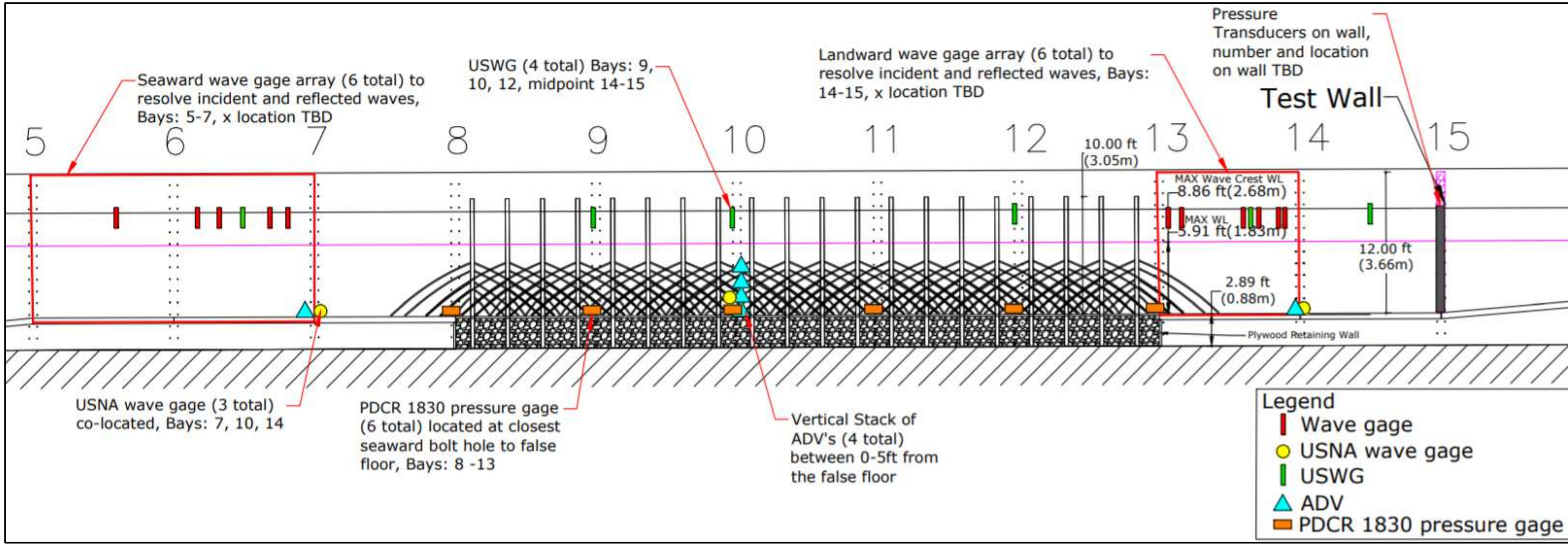


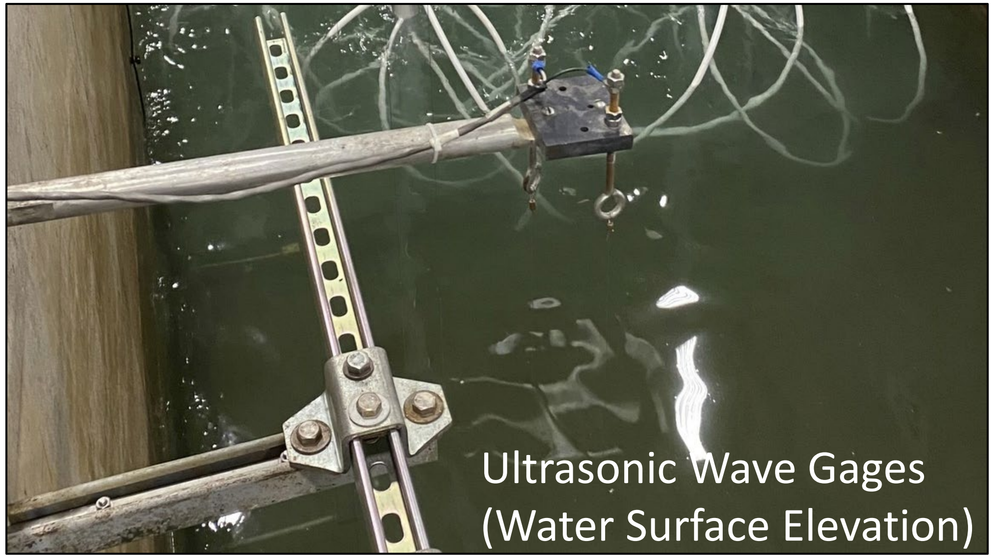
$$\tilde{\alpha} = \frac{\overline{A_t} \cdot N \cdot H_{rms,i} \cdot C_D \cdot k_p}{3\sqrt{\pi}} \cdot \frac{\left(\sinh\left(k_p l_d\right)\right)^3 + 3\sinh\left(k_p l_d\right)}{\sinh\left(k_p h\right)\left[\sinh\left(2k_p h\right) + 2k_p h\right]}$$

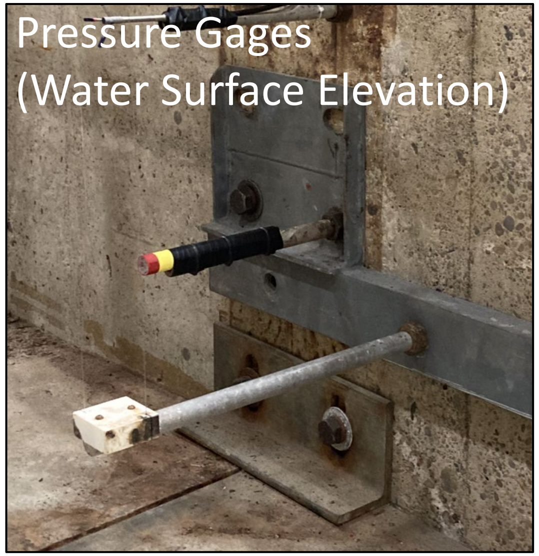
- Accurate to within 2% of known stem diameters, 10% of known root diameters
- Allows full characterization of vertical variation of projected area, uncertainty

Instrumentation



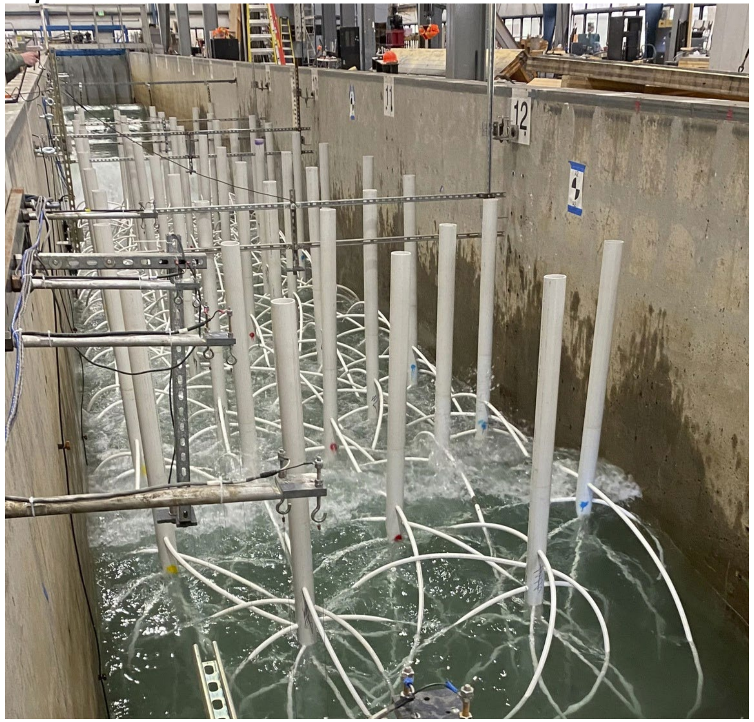


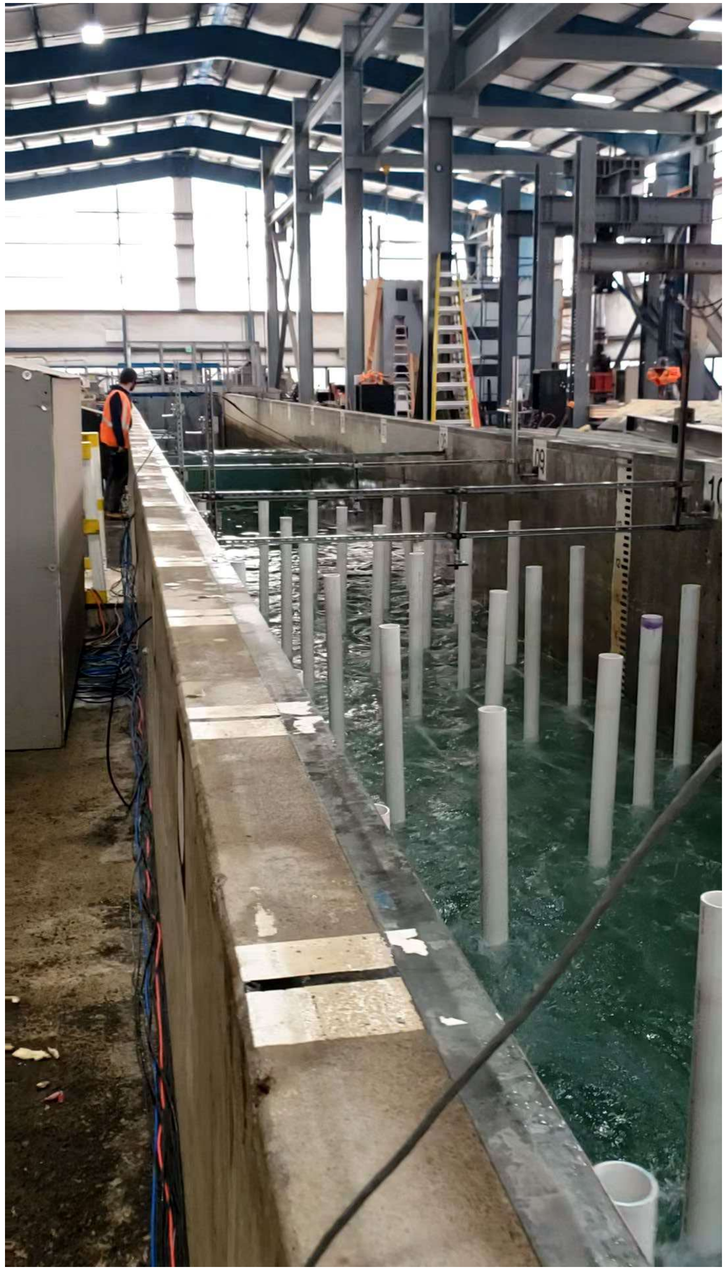




Mangrove Effects on Hydrodynamics

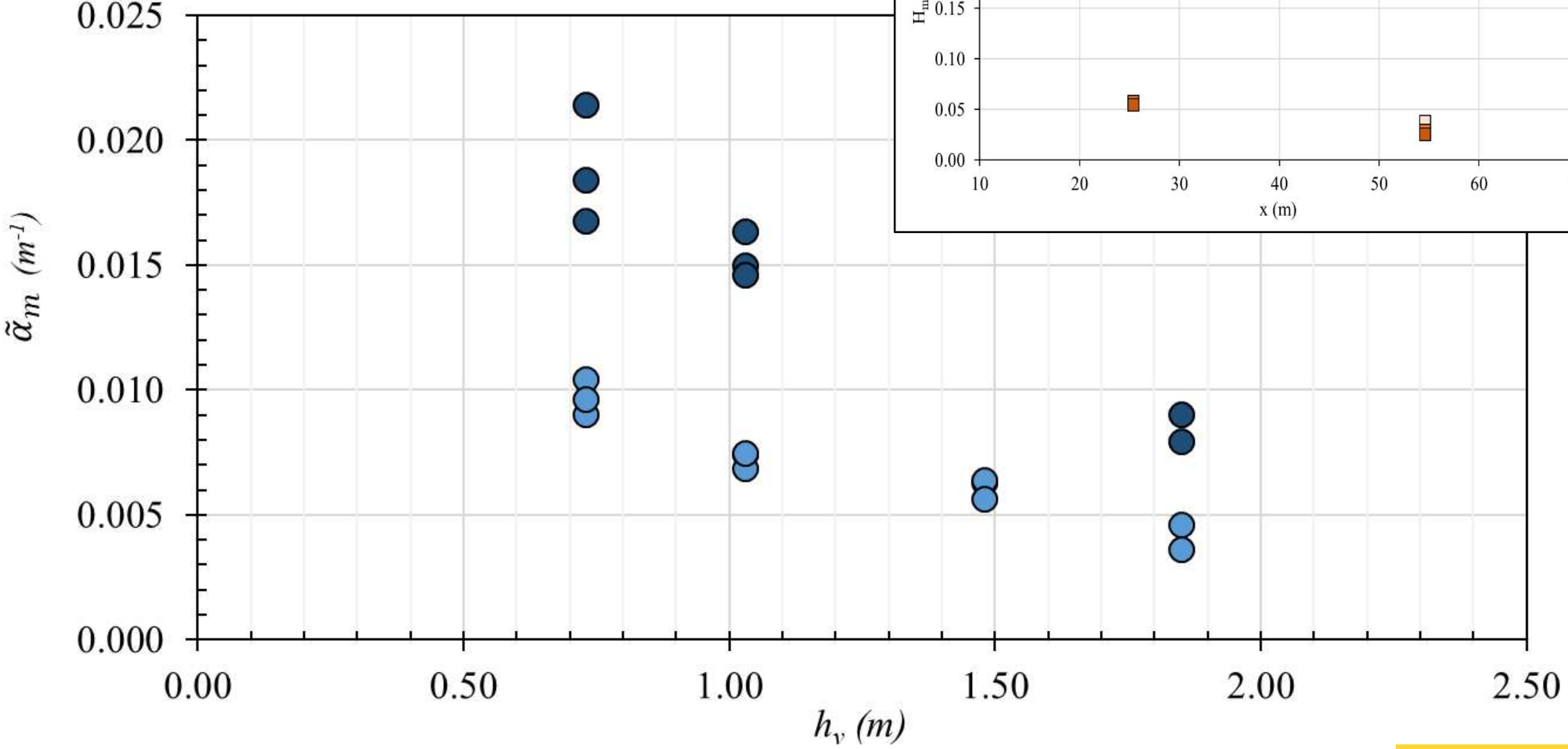
- 4 water depths tested
  - h_{veg} = 0.70 m to 1.82 m
- Irregular and regular wave conditions
  - $H_{i,m0}$ = 0.1 m to 0.73 m
  - T_p = 1.91 s to 7.45 s

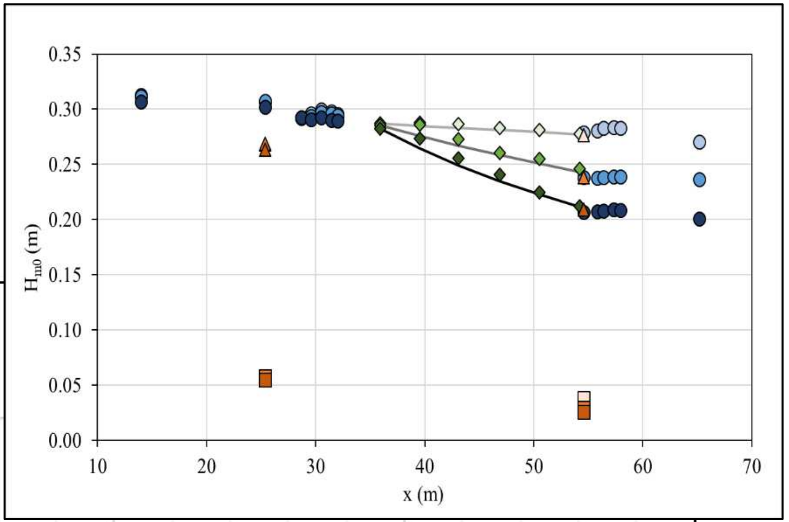




Empirical Wave Height Decay Coefficients

$$\frac{H_t}{H_i} = \frac{1}{1 + \tilde{\alpha} x}$$

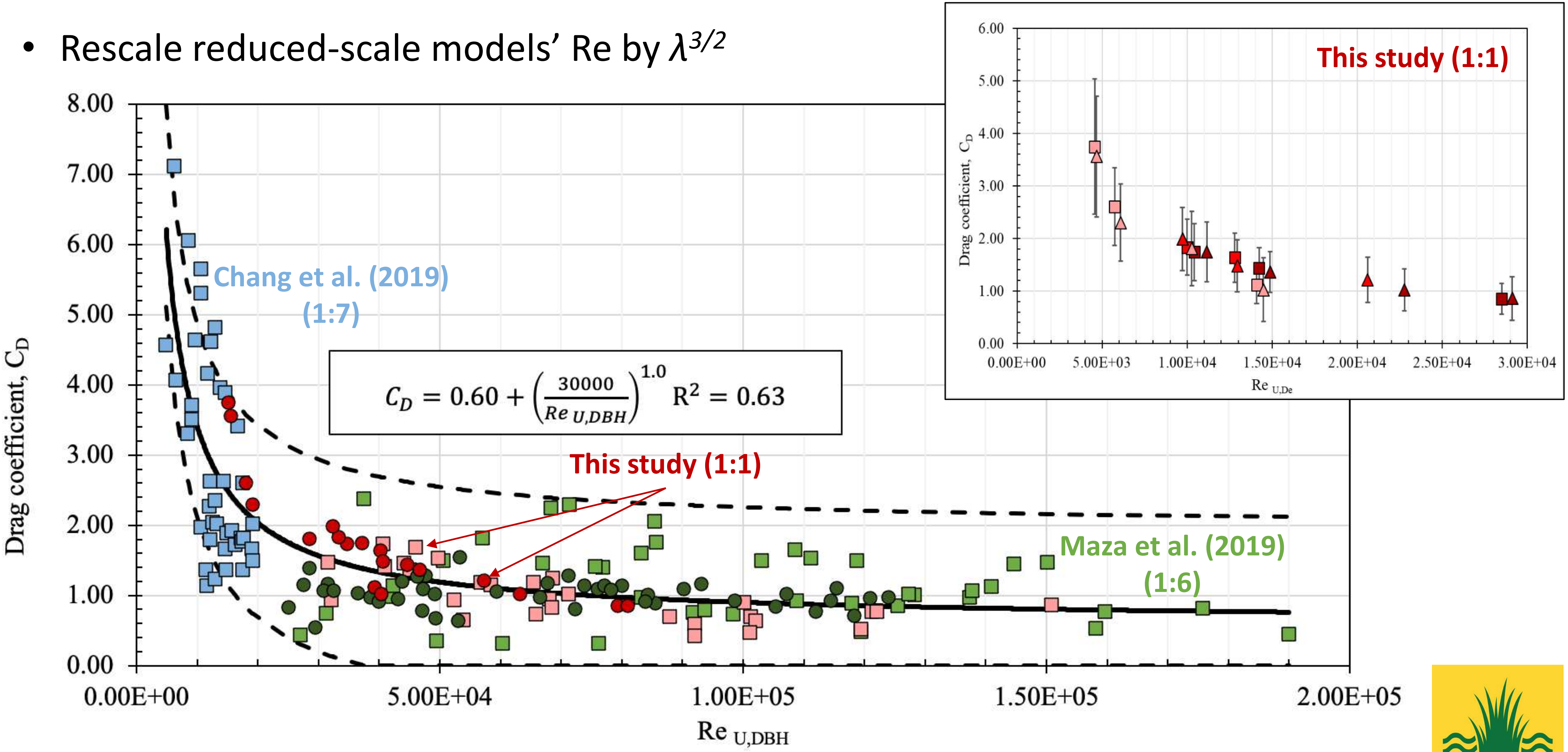




- Decay coefficients are a function of water depth
- Doubling forest density increased decay rate by factor of ~2

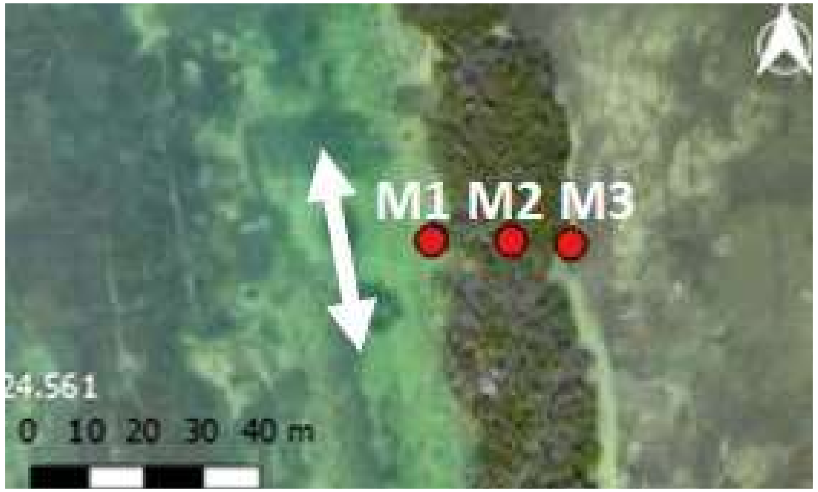
Drag Coefficient Including Uncertainty

- Rescale reduced-scale models' Re by $\lambda^{3/2}$



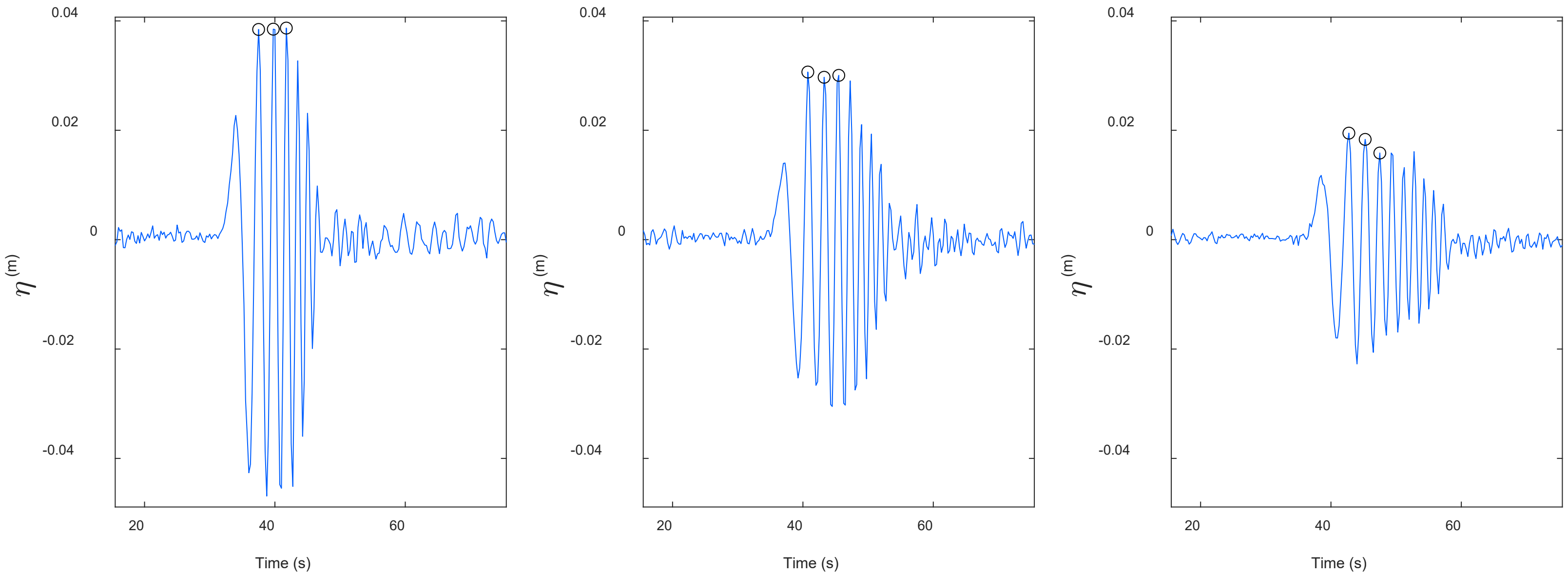
Kelty, K., Tomiczek, T., Cox, D., Lomonaco, P., and Mitchell, W. Prototype-Scale Physical Model Study of Wave Attenuation by a Mangrove Forest of Moderate Cross-shore Thickness: LiDAR-based Characterization and Reynolds Scaling for Engineering With Nature. Frontiers In Marine Science, Revisions Submitted.

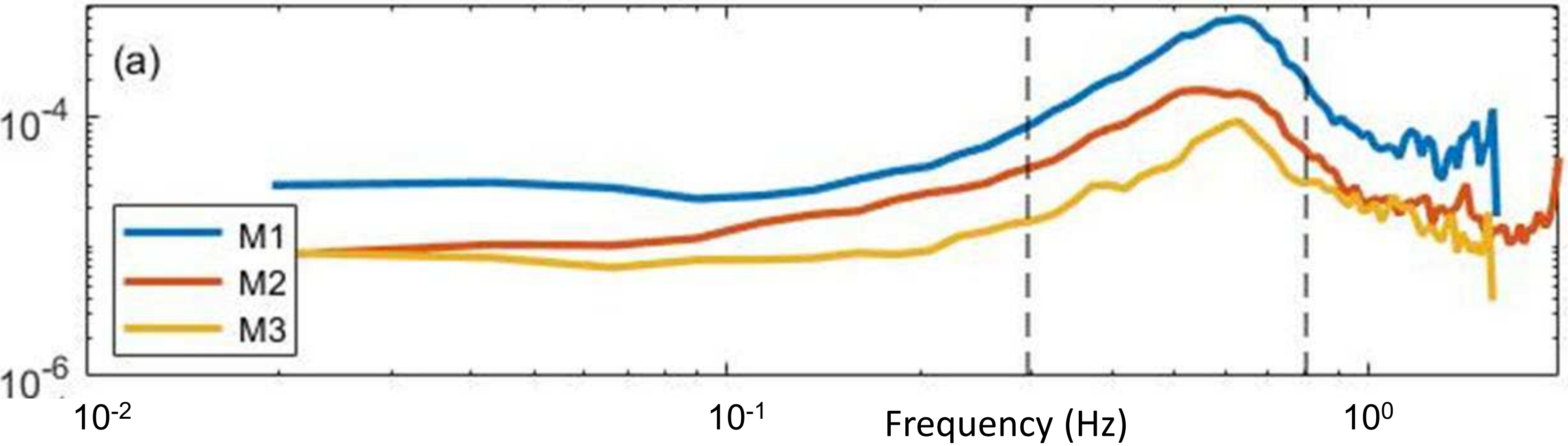
Field-Based Monitoring: Vessel-Generated Wake Attenuation by Mangroves

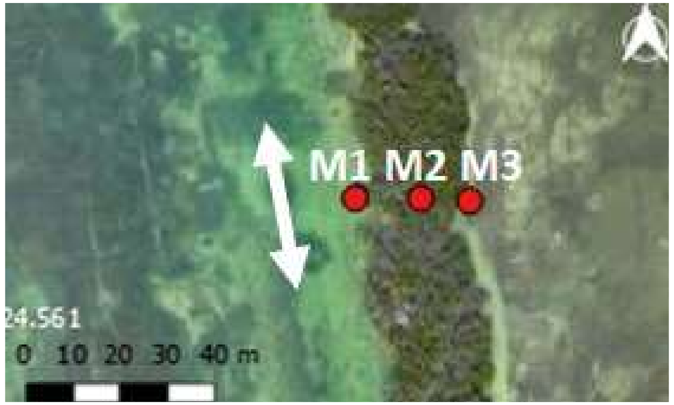


- Measured 236 vessel-generated wakes at fringe (M1), middle (M2), and rear (M3) of a 12.6 m mangrove island
- Transmission coefficients calculated at middle and rear
- Wave transformation due to mangroves (energy dissipation), bathymetry (depth/flow over LCS)

Vessel-Generated Wake Attenuation







- Wave height decreases from fringe to middle to rear
- Spectral energy decreases
  - Greater reduction more for shorter period waves, higher incident wave heights
- Separate bathymetric and mangrove contributions using analytical solutions

Tomiczek, T., Wargula, A., O'Donnell, K., LaVeck, K., Castagno, K., and Scyphers, S. 2022. Vessel-generated Wake Attenuation by *Rhizophora Mangle* in Key West, FL. Journal of Waterway, Port, Coastal, and Ocean Engineering, In Press., https://doi.org/10.1061/(ASCE)WW.1943-5460.0000704.

Monitoring Wind-Wave Attenuation By Mangroves

- Sensors deployed 16 AUG – 14 OCT 2021, 15 OCT – 5 JAN 2022
- Sampling Rate: 8 Hz
- Field protocol to characterize sites for engineering protection

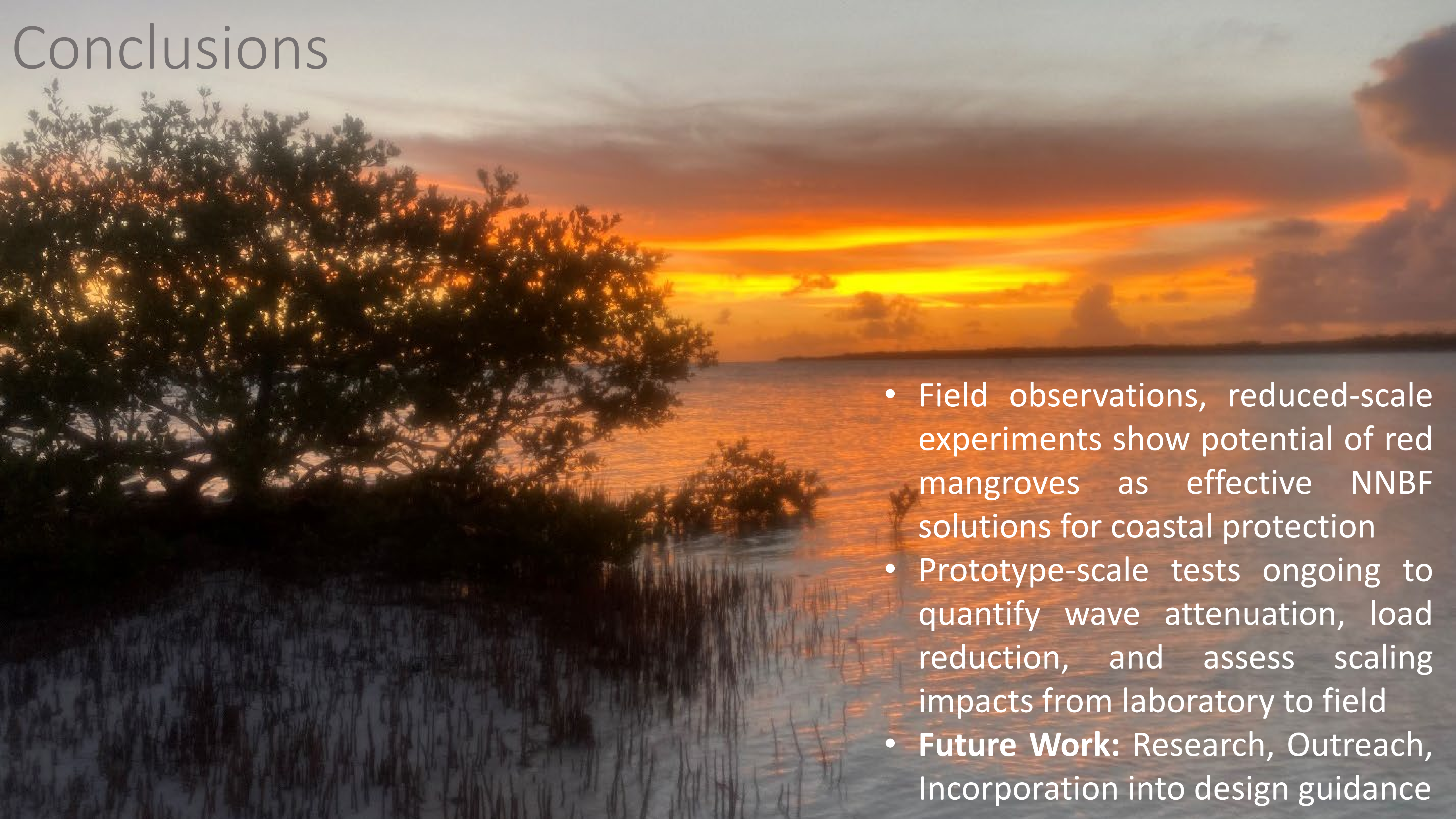
Modeling Capabilities

Computational Effort / Level of Physics Included		**High** →								**Medium**			**Low**
Type of Model		**RANS**			**Other Phase Resolving**				**Phase Averaging**			**Overland**	**Empirical**
Model Name		**OpenFOAM**		**NHWAVE**	**SWASH**	**COULWAVE**	**XBeach**		**SWAN**		**STWAVE**	**WHAFIS**	**WATTE**
Model Reference		Jasak et al., 2007; Higuera et al., 2014		Ma et al., 2012	Zijlema et al., 2011	Lynett et al., 2002	Roelvink et al., 2009		Booij et al., 1999		Smith et al., 2001	FEMA, 2021	Foster-Martinez et al., 2020
Processes Included		Wave, Nearshore Circulation		Wave, Nearshore Circulation	Wave, Nearshore Circulation	Wave, Nearshore Circulation	Wave, Nearshore Circulation		Wave		Wave	Wave	Wave
Approach	Vegetation Reference	Maza et al., 2015; 2016 "Microscopic"	Maza et al., 2015 "Macroscopic"	Ma et al., 2013	Suzuki et al., 2019	Yang et al., 2018	van Rooijen et al., 2016 Non-hydrostatic	van Rooijen et al., 2016 Surfbeat[1]	Jacobsen et al., 2019	Suzuki et al., 2012	Anderson and Smith, 2015	FEMA, 2021	Foster-Martinez et al., 2020
	Underlying Equation for Vegetation	N/A	Morison-type	Morison-type	Morison-type	Morison-type	Morison-type	Mendez and Losada, 2004	Morison-type	Mendez and Losada, 2004	Mendez and Losada, 2004	Modified NAS, 1977	Kobayashi et al., 1993
	Flexibility	Y		Y	N	N	N		N		N	Y	N
	Inertial Force	Y		Y	Y	N	N		N		N	N	N
	Layering	Y		Y	Y	N	Y		N	Y	N	N	N
	Horizontal Cylinders	Y		N	Y	N	N		N		N	N	N
	Canopy and Porosity Hydrodynamics	Y	Porosity incorporated as modified k-ε and drag force	Canopy flow through turbulence	Porosity, Canopy flow converted to TKE	N	Porous in-canopy flow		Nonlinearity in canopy flow	N	N	N	N
	Maximum Dimensionality	3D		3D	3D	2D	2D		2D		2D	1D	1D

- Many numerical models use Mendez and Losada (2004), other drag-coefficient for vegetation
- Need to validate with large-scale models, field observations

Ostrow, K., Guannel, G., Biondi, E.L., Cox, D., and Tomiczek, T. State of the Practice and Engineering Framework for Using Emergent Vegetation in Coastal Infrastructure. *Frontiers in the Built Environment,* in review.

Conclusions



- Field observations, reduced-scale experiments show potential of red mangroves as effective NNBF solutions for coastal protection
- Prototype-scale tests ongoing to quantify wave attenuation, load reduction, and assess scaling impacts from laboratory to field
- **Future Work:** Research, Outreach, Incorporation into design guidance

Thank you!

Contact: Tori Tomiczek, vjohnson@usna.edu

Questions?

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- Executive Summary (70 pages)
- International Guidelines on NNBF for Flood Risk Management (1,000 pages)