A Process-Based Model for Forecasting Wave Runup along the Coast of Georgia

Robert Fiegelist[1], Matthew V. Bilskie[1]
DL Passeri[2] & C.B. Woodson[1]

[1]University of Georgia, College of Engineering
[2]USGS, St. Pete Coastal & Marine Science Center

3rd International Workshop on
Waves, Storm Surges, and Coastal Hazards
South Bend, IN
Oct. 1 - 6, 2023

Outline

- Research Objectives
- Background
- Methods
- Results
- Discussion
- Conclusions

Research Objectives

1. To develop a method for forecasting wave runup that accounts for detailed site-specific topo-bathy in a wave-resolving process-based model.
2. To effectively implement a method for measuring wave runup using pressure sensors and RTK equipment.

Background

Measuring Wave Runup

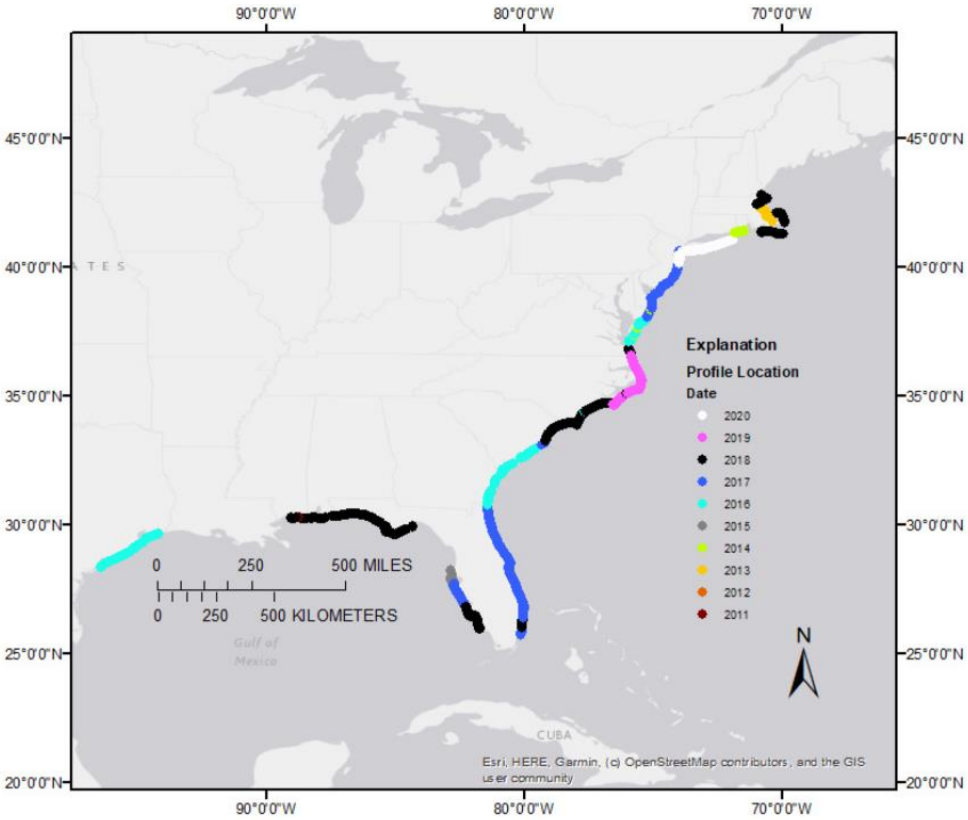
- Imagery
    - Pros: Cost-effective; Continuous data collection
    - Cons: Complex post-processing; limited to good lighting conditions
- Sensors
    - Pros: Measure swash energy; Temporally continuous
    - Cons: Cost; Deployment Logistics

Simulating Wave Runup

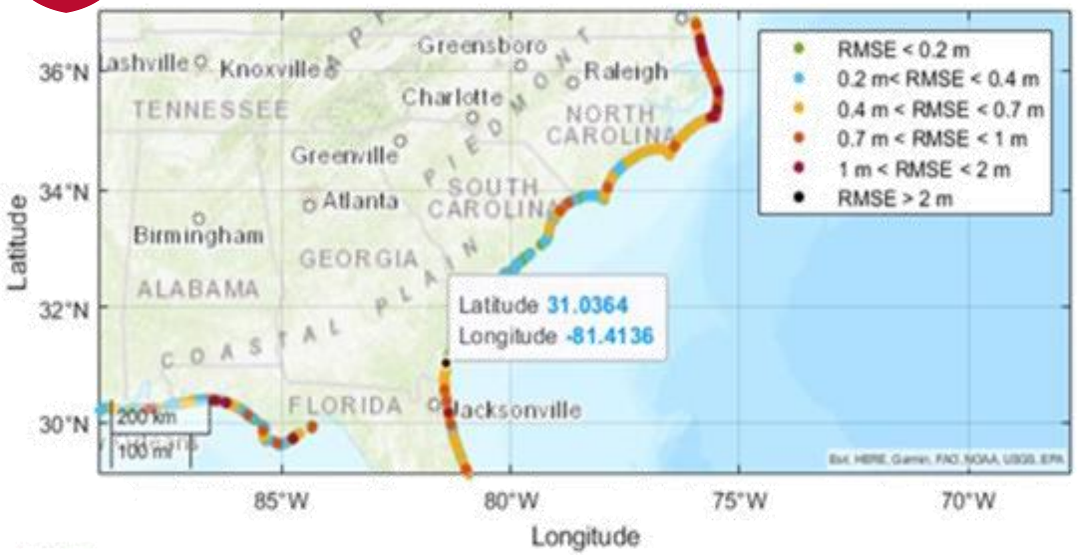
- Empirical Methods
    - Stockdon (2006)
    - Site bias; Generalization of beach profile
- Numerical Methods
    - XBeach; Computationally Expensive

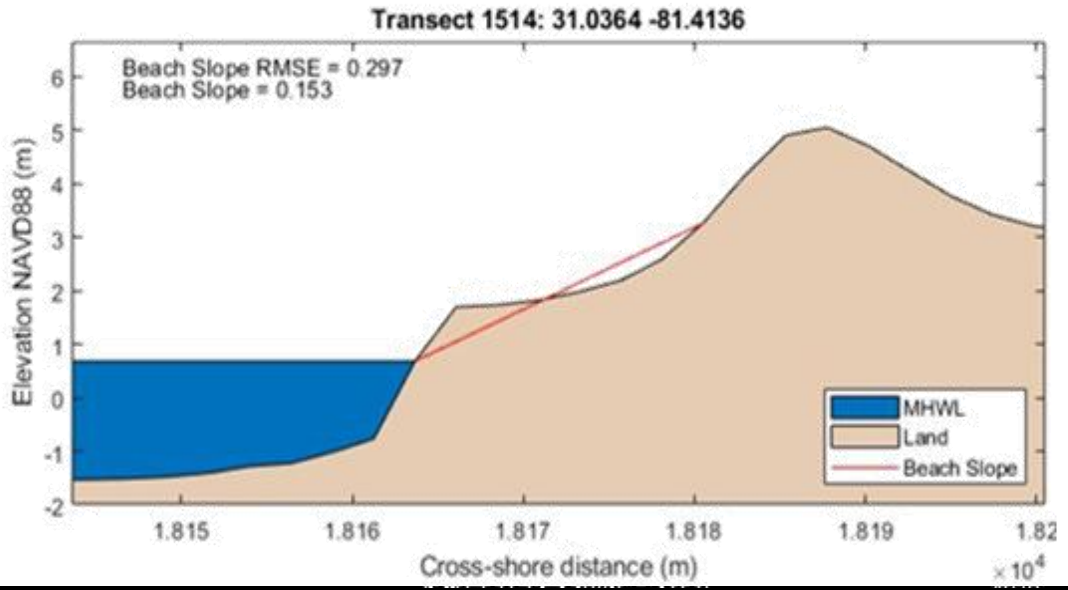
Background: Importance of Importance of Topo-bathy

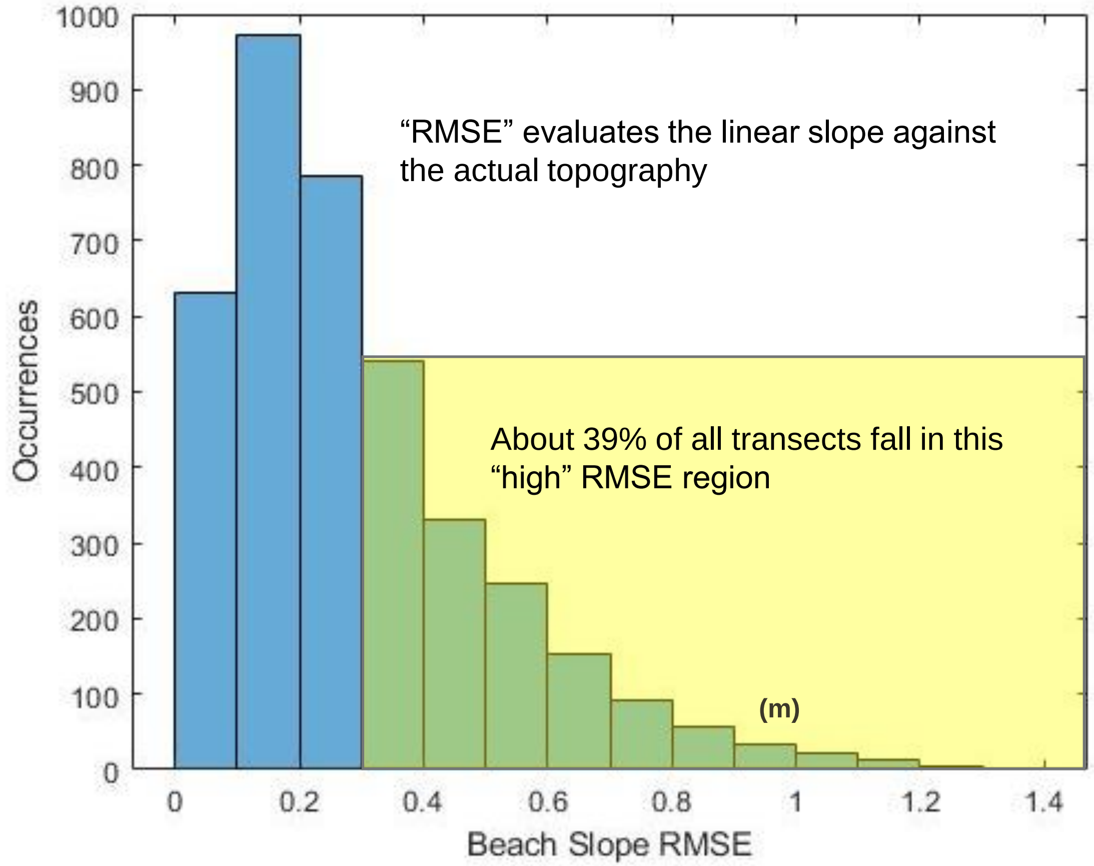
- Not always one uniform slope for a beach profile
- Tidal level increases the complexity of calculating wave runup but is not accounted for in many empirical parameterizations [16]
- Nearshore bathymetry is just as impactful [17] [18]
- Profile shape and characteristics (Beach and dune width, dune height, etc.) all affect morphology [19], and therefore hydrodynamics in XBeach runs.
    - Tied to storm magnitude
- Data set of approximately 4,000 Topo-Bathy Cross-Shore Profiles [20]
    - Diverse in shape, slope, dunes, etc.
    - Gathered from the most recent lidar data that was available at the time of publishing
    - Not idealized or hypothetical profiles (to the extent that is possible)
    - Valuable source for running simulations at site-specific locations.



[16] (Guedes et al., 2011)
[17] (Cohn et al., 2014)
[18] (Cohn & Ruggerio, 2016)
[19] (Mickey et al., 2020)
[20] (Mickey and Passeri, 2022)

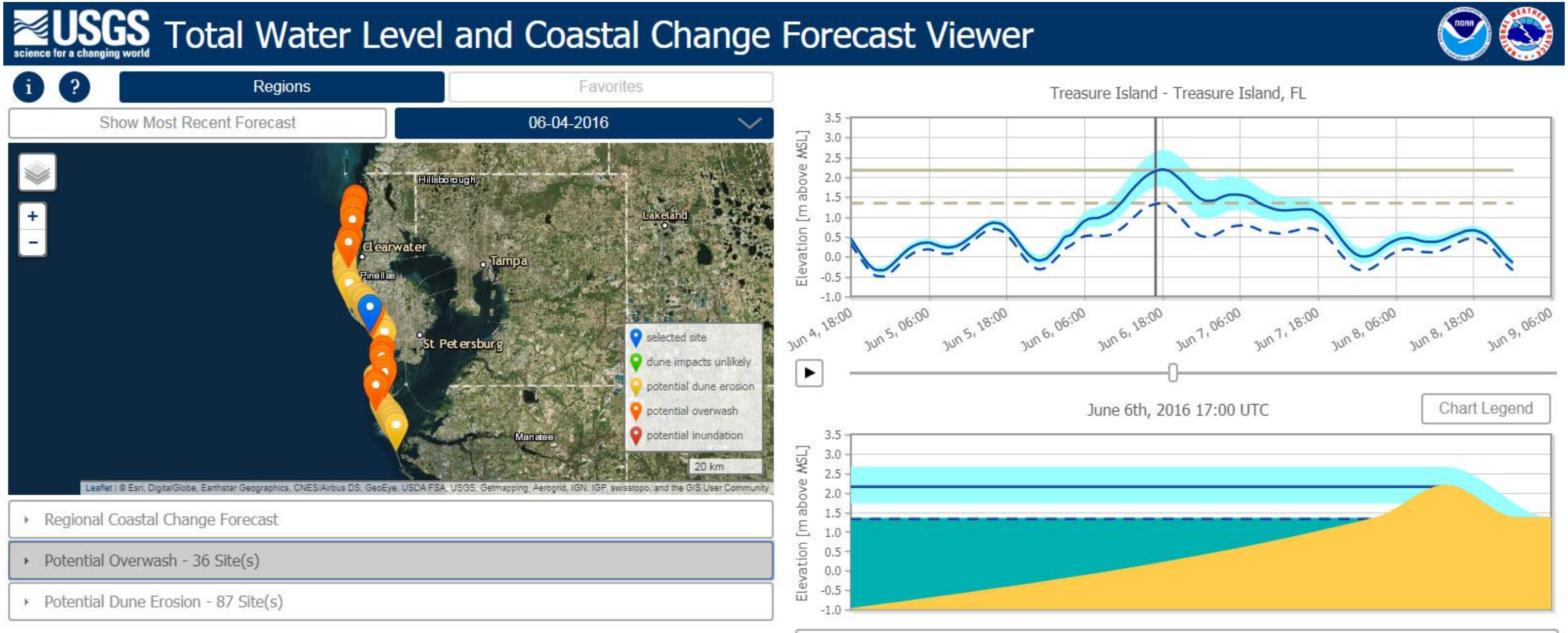






*30 cm is approximately 13% of Georgia's tidal range

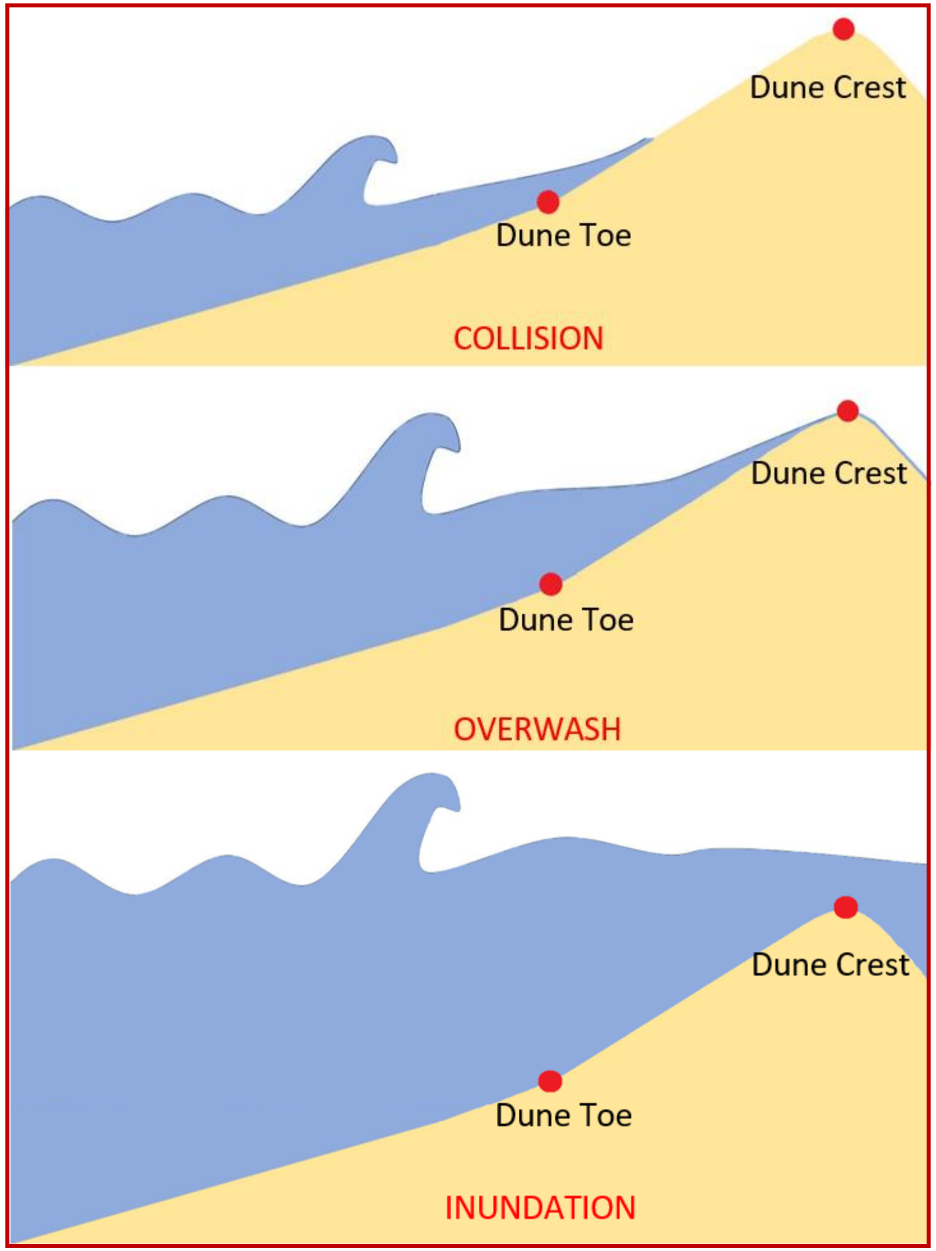
Coastal Hazard Forecasting



Time of Peak TWL [UTC]	Tide + Surge @ Peak TWL [m]	Wave runup @ Peak TWL [m]	Peak TWL [m]	Dune Toe Elev. [m]	Dune Crest Elev. [m]
06-06-2016 18:00	0.9	1.29	2.19	1.34	2.17

Impact Regimes

- Collision: TWL > Dune Toe
- Overwash: TWL > Dune Crest
- Inundation: SWL + wave setup > Dune Crest



(Sallenger, 2000)

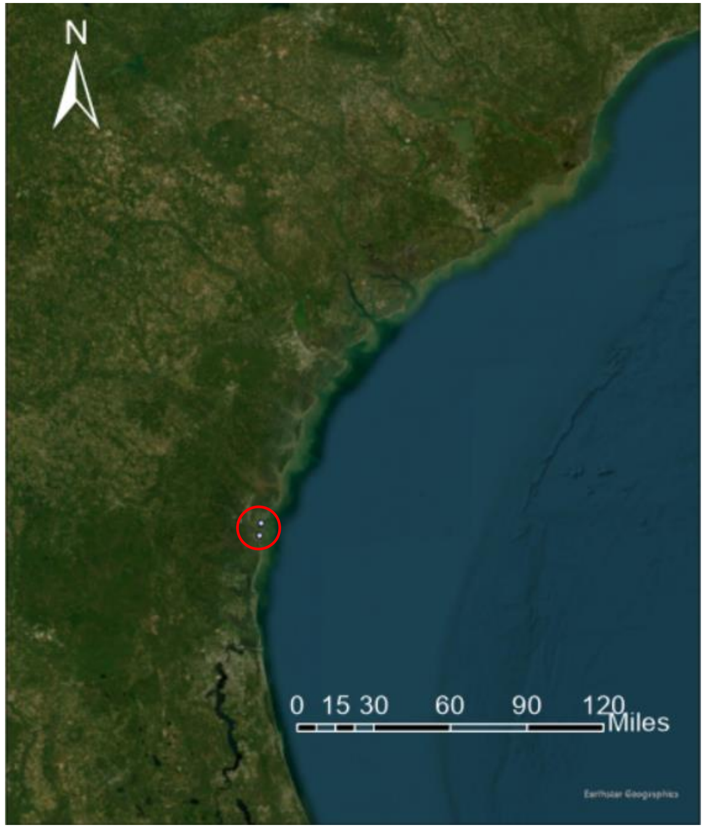
Methods – Numerical Model

- XBeach non-hydrostatic (XBNH) uses the Non-Linear Shallow Water Equations with a pressure correction term
- It fully resolves short and infragravity waves in intermediate and shallow water and enables wave-breaking when a required steepness is achieved (Quataert et al., 2020)
    - More computationally expensive than the phase-averaging version, but shown to be better hydrodynamically
- The 2-layer setting used in this study (*nhq3d = 1*) assumes constant pressure in the lower layer, improving dispersion and extending XBNH applicability into more intermediate depths (de Ridder et al., 2021)
- Horizontal grid Resolution: *dx max = 5 m* and *dx min = 0.25* m for every point above the MLLW datum
- To satisfy the required cells per wavelength in the offshore region (recommended 25-50), the wave period of the simulation was also inputted into the grid function

Methods - Jekyll Island Runup Experiment

Study Site

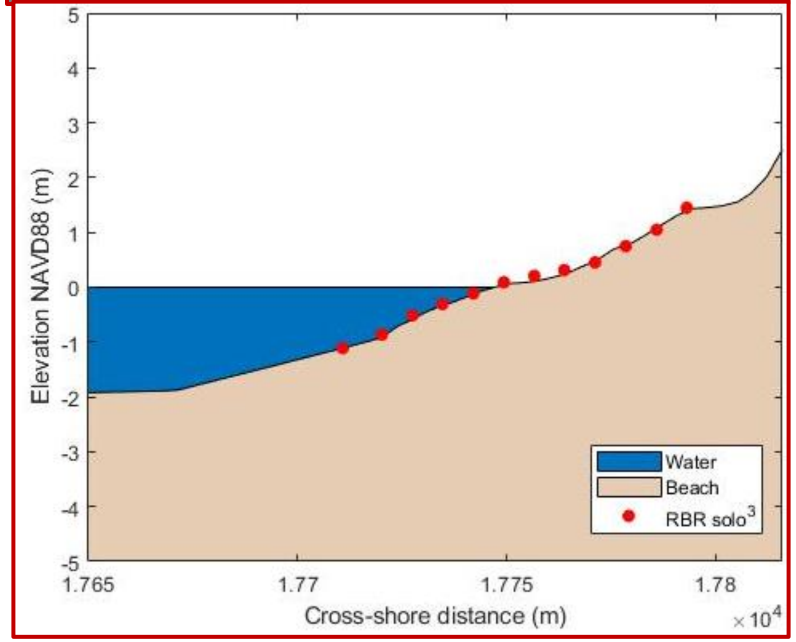
- Jekyll Island, GA– about 50 miles north of Jacksonville, FL
- State Park with limited foot traffic on beaches
- Semidiurnal tides and sandy beaches

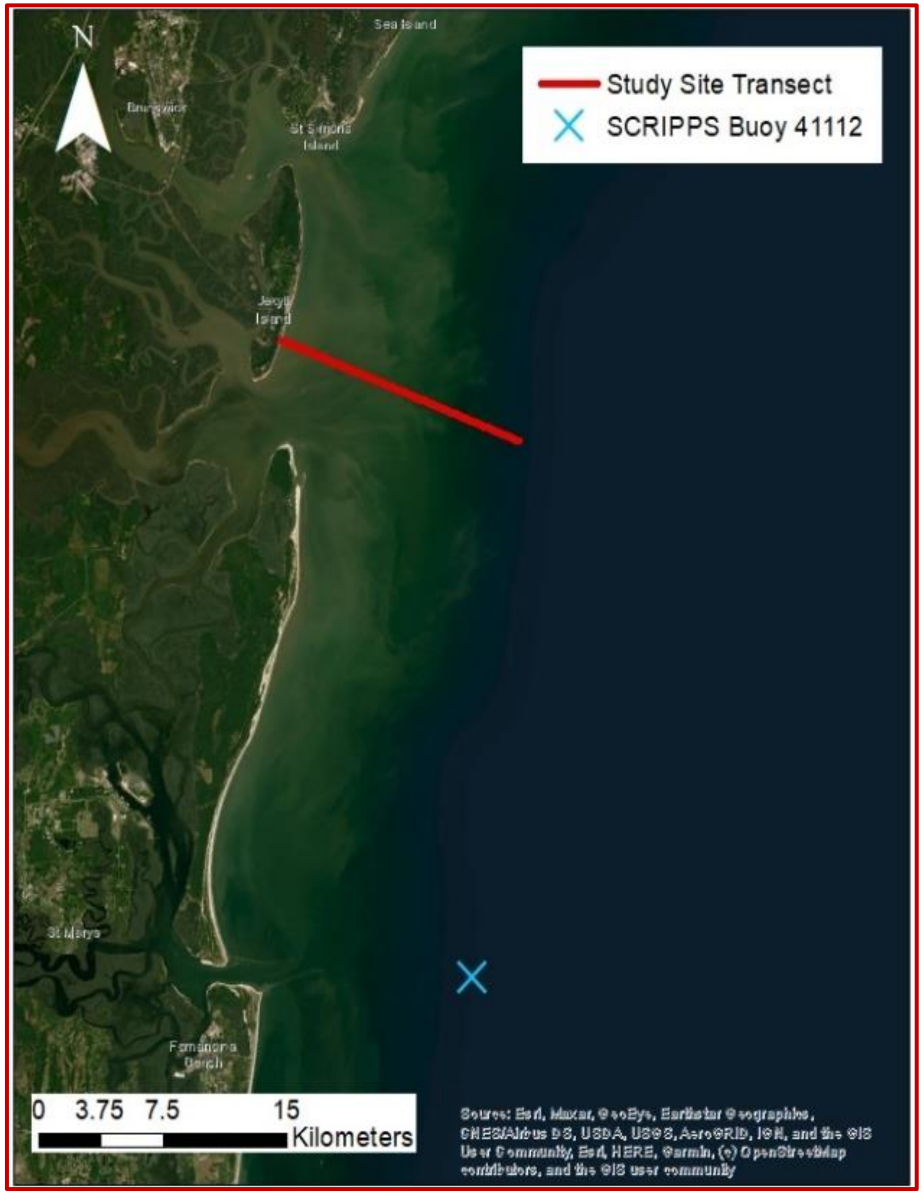


Methods - Jekyll Island Runup Experiment

- 12 pressure sensors measuring at 2 Hz (8 in x 2 in.)
  - Mounted and placed bed-level with geofabric to keep sand out of the sensor
  - Spaced throughout the tidal range and left to collect data for ~24 hours
  - Most offshore sensor was fully submerged for the full duration to monitor the SWL
- Trimble DA2 RTK equipment with < 2 cm vertical accuracy
  - Each sensor's elevation is noted and a profile of the beach was surveyed

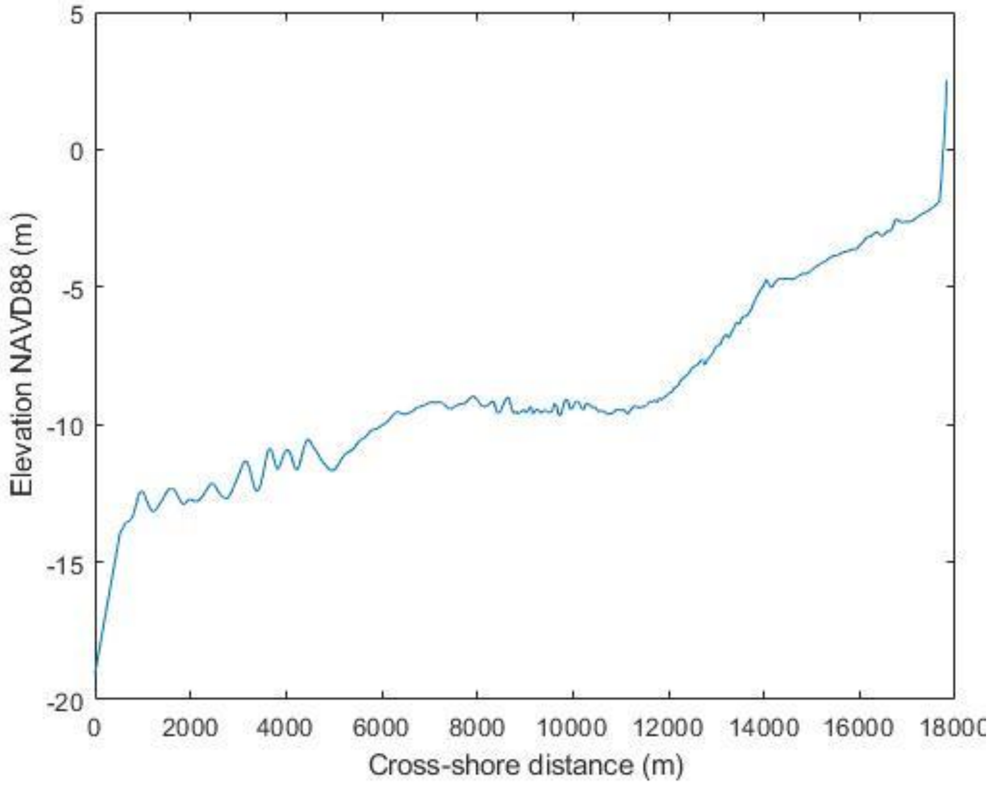
Sensor layout





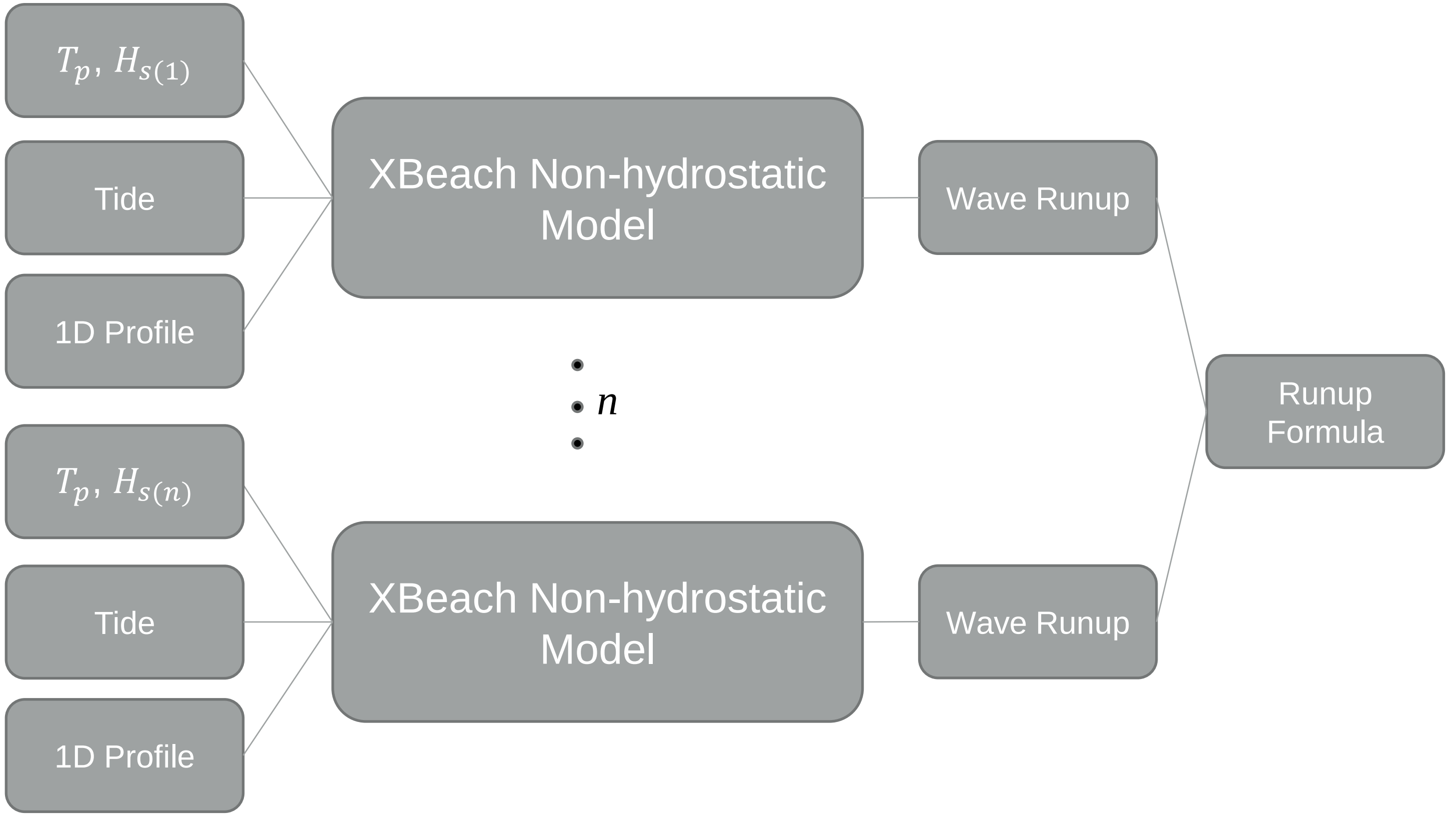
XBeach Inputs

- Wave inputs from NDBC Buoy 41112
    - Wave height and wave period
- Tide input from the fully submerged sensor
- Topo-bathy from beach survey coupled with nearest transect from Mickey and Passeri, 2022 dataset

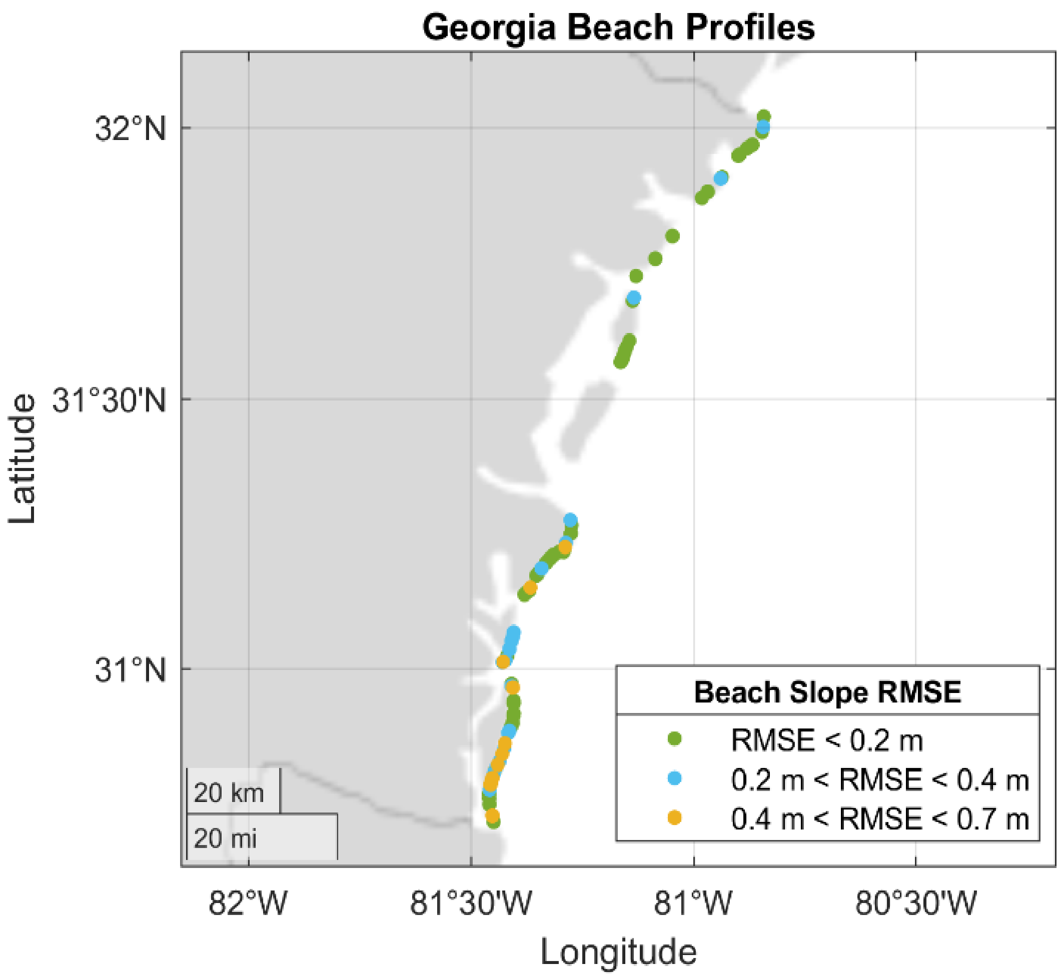


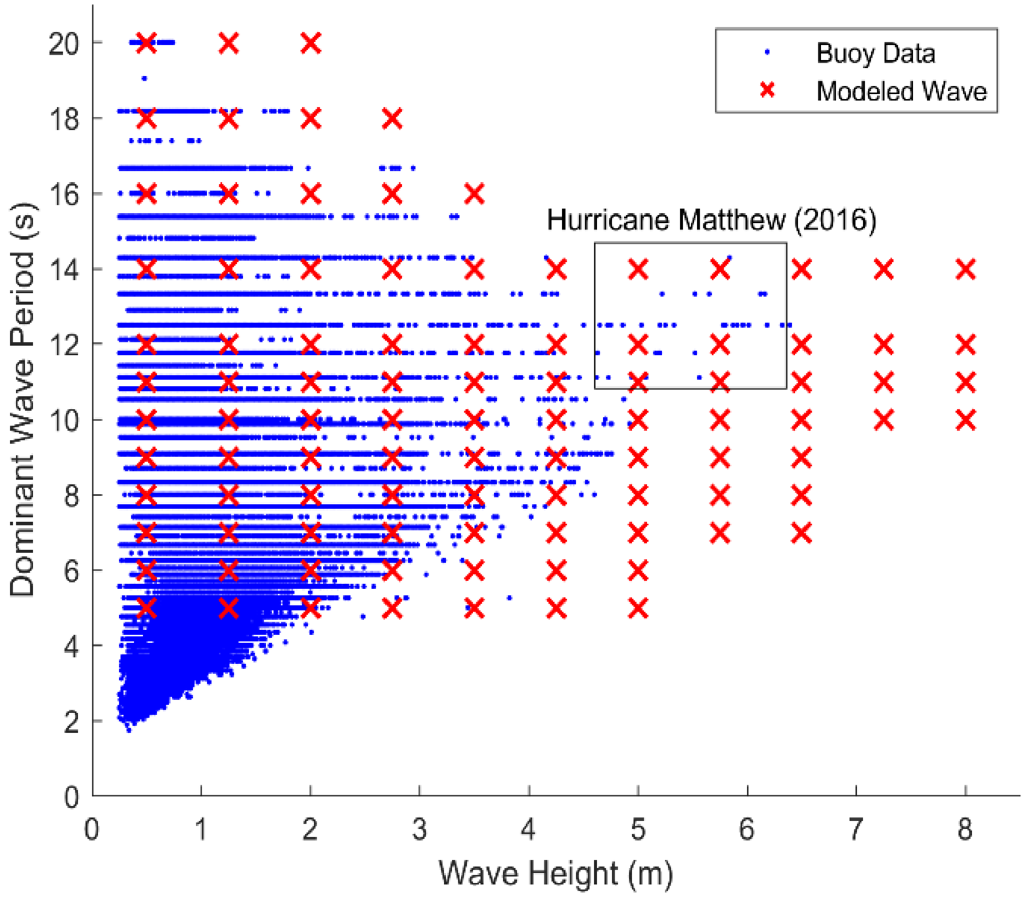
Methods – Generating Wave Runup Equations with XBNH

- Run model for varying wave conditions
- Run at three datums
  - MLLW, MHHW, Surge = 2 m
- Extract 2% exceedance of water level time series local maxima
- Interpolate results to fit polynomials that can be used to forecast runup based on wave conditions
- Repeat for all transects of interest



Methods – Generating Wave Runup Equations with XBNH



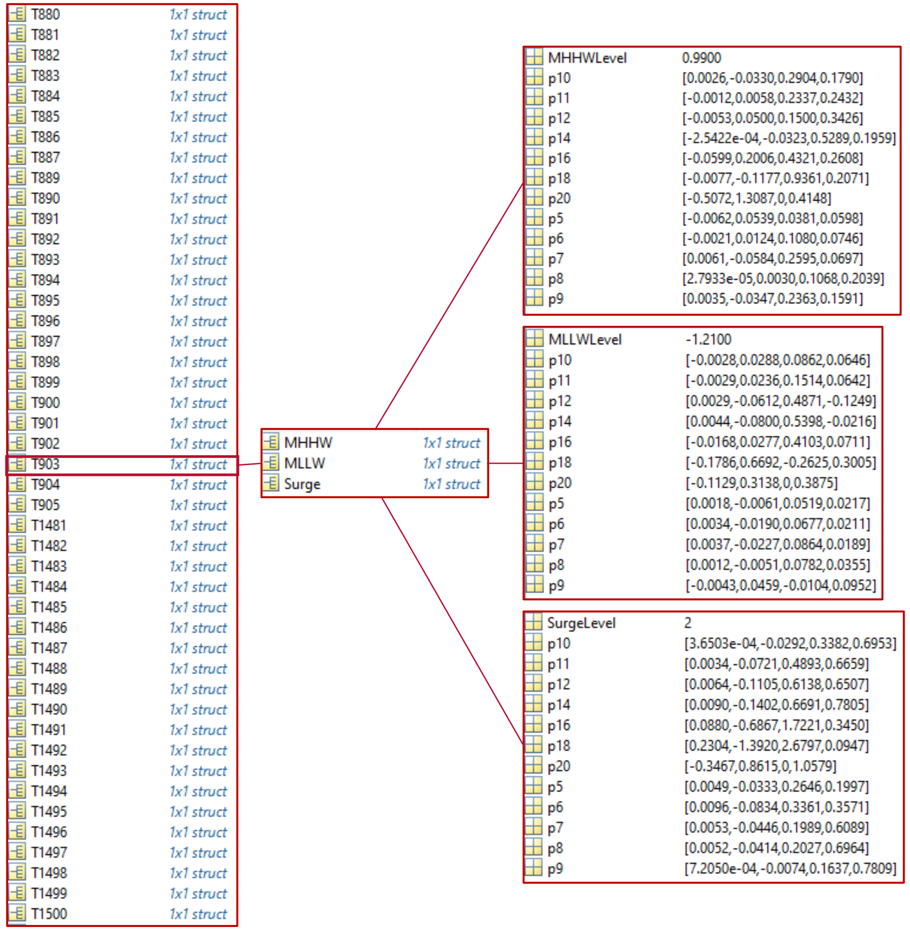


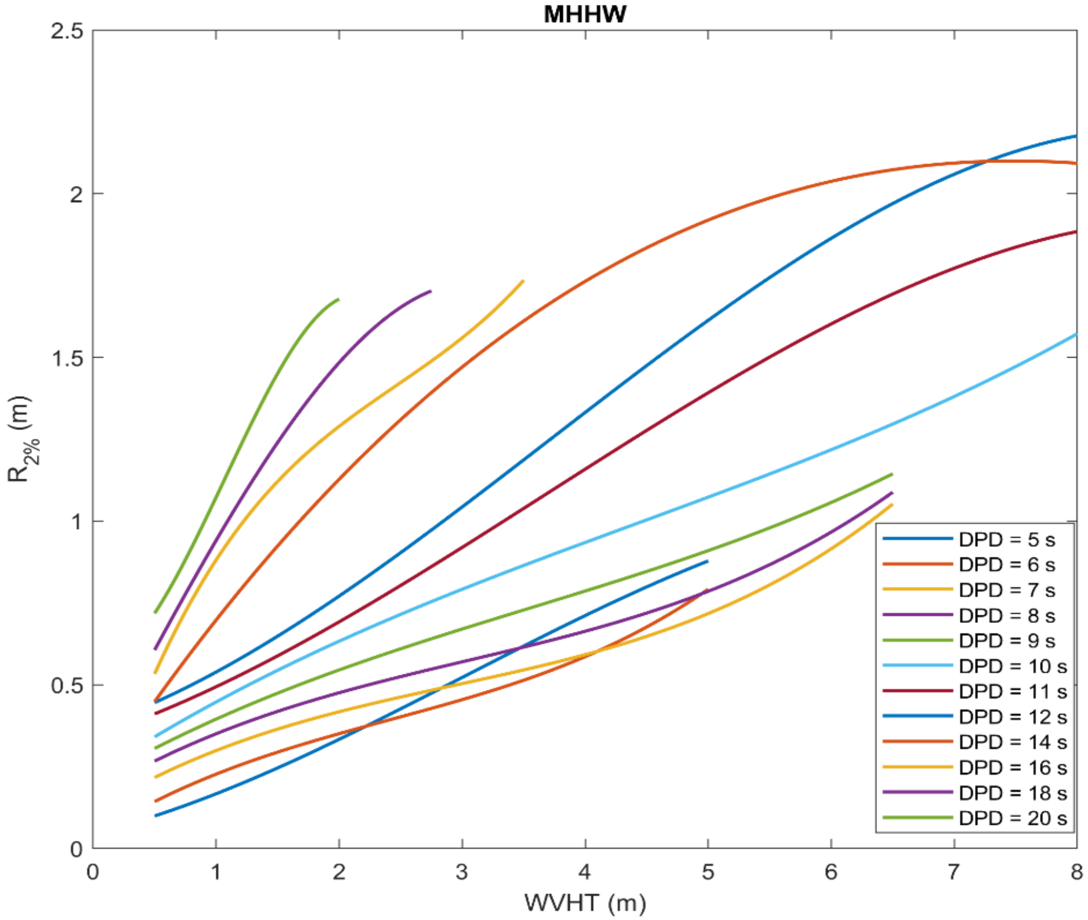
Methods - Generating TWL and Runup Forecasts

- The TWLCC Viewer has an API that provides access to wave conditions, TWL, runup, tide, setup, beach slope, dune crest, impact regime, and other parameters.
    - Each location in this study has a corresponding location in the API
    - The wave height, period, tide, and wind setup are extracted for the desired time range
- If the wave period is not exactly one of the modeled wave periods, runup is linearly interpolated between the closest two wave period equations.
- The calculated runup value depends on the tide and wind setup for that time in the forecast
- The calculated wave runup is added to the API's tide and wind setup but does not include the API's wave setup.
- A classification of “none”, “collision”, “overwash”, or “inundation” is then determined based on the TWL and the dune toe and crest elevations from the beach profile.

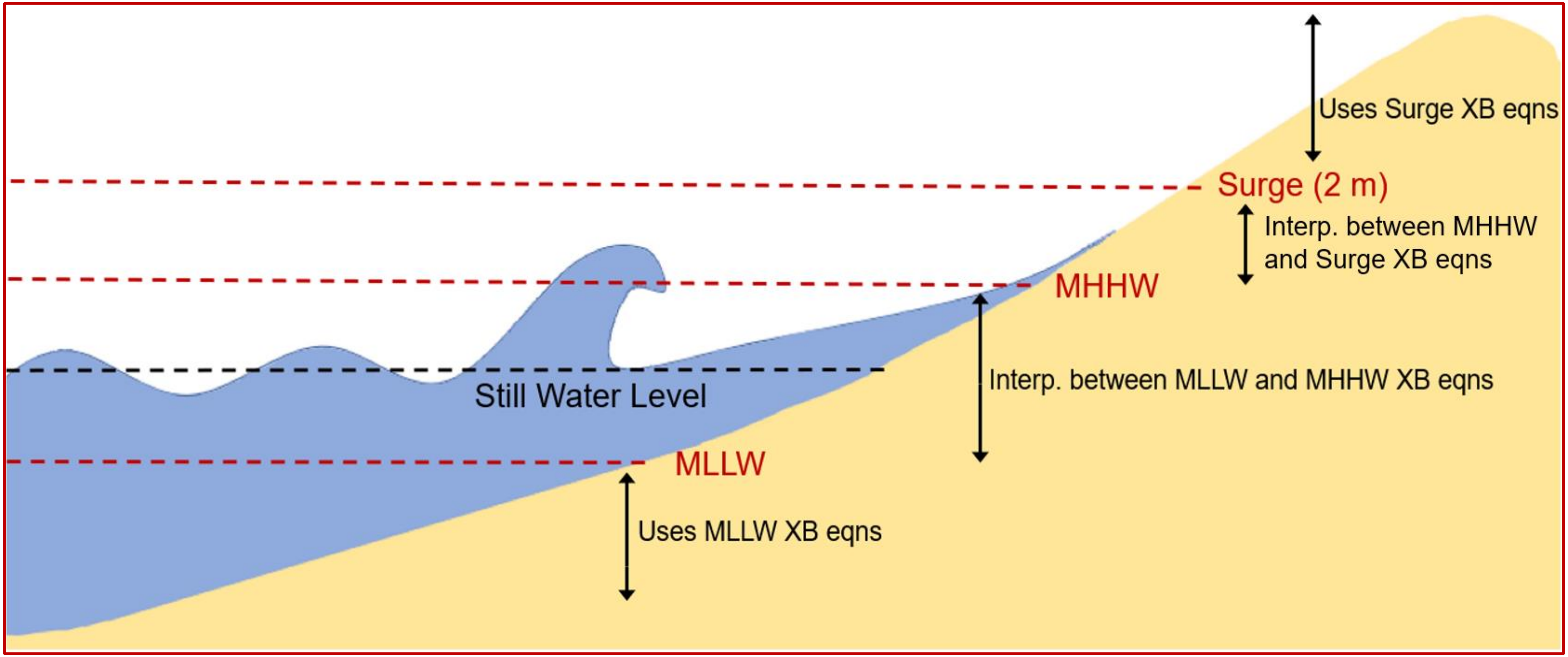
Methods - Generating TWL and Runup Forecasts

- Three sets of equations based on tidal datum for each transect

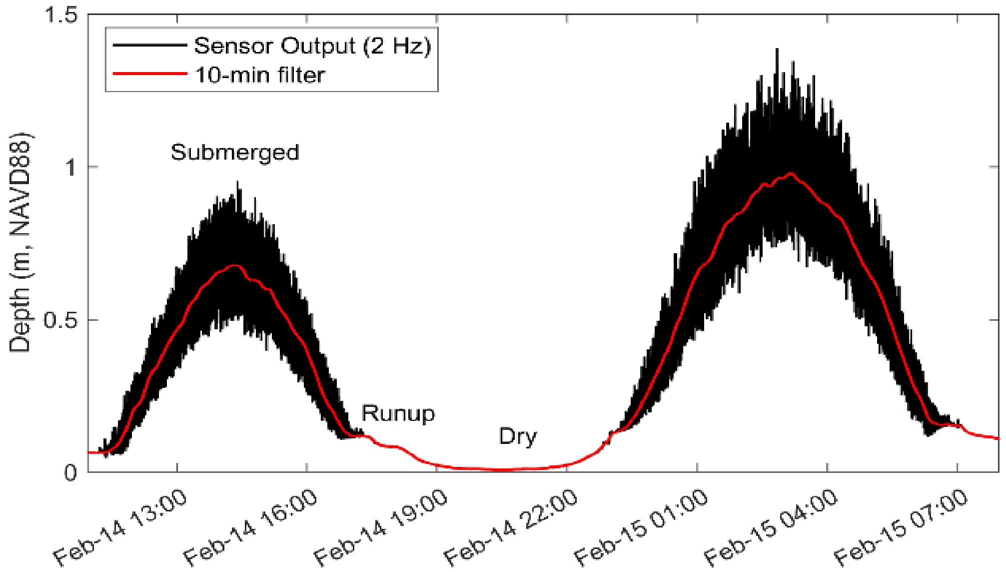


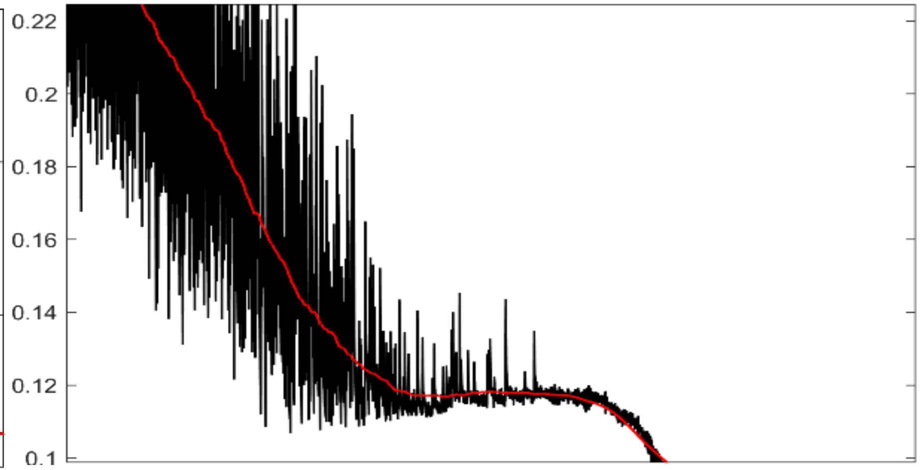


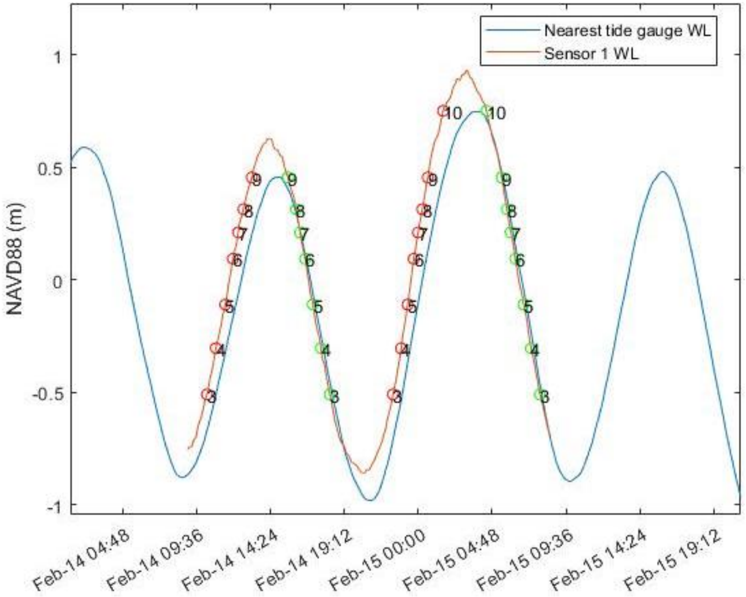
Methods - Generating TWL and Runup Forecasts

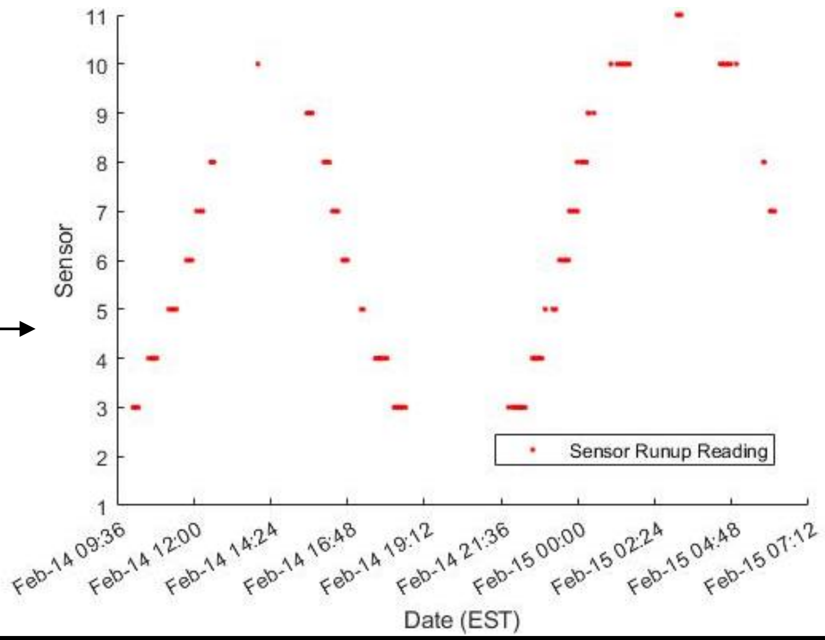


Results – Jekyll Island Field Experiment



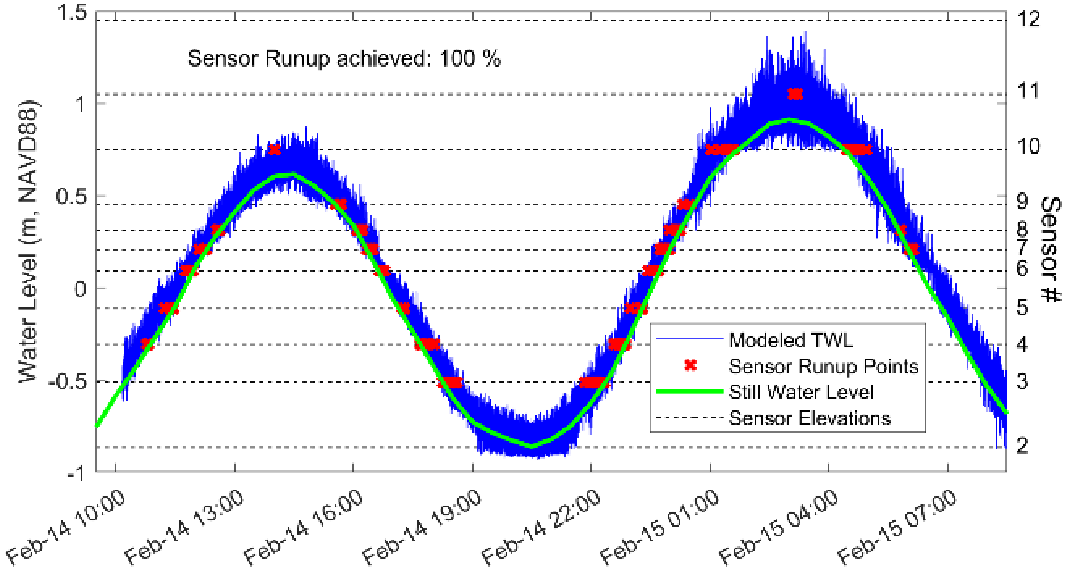


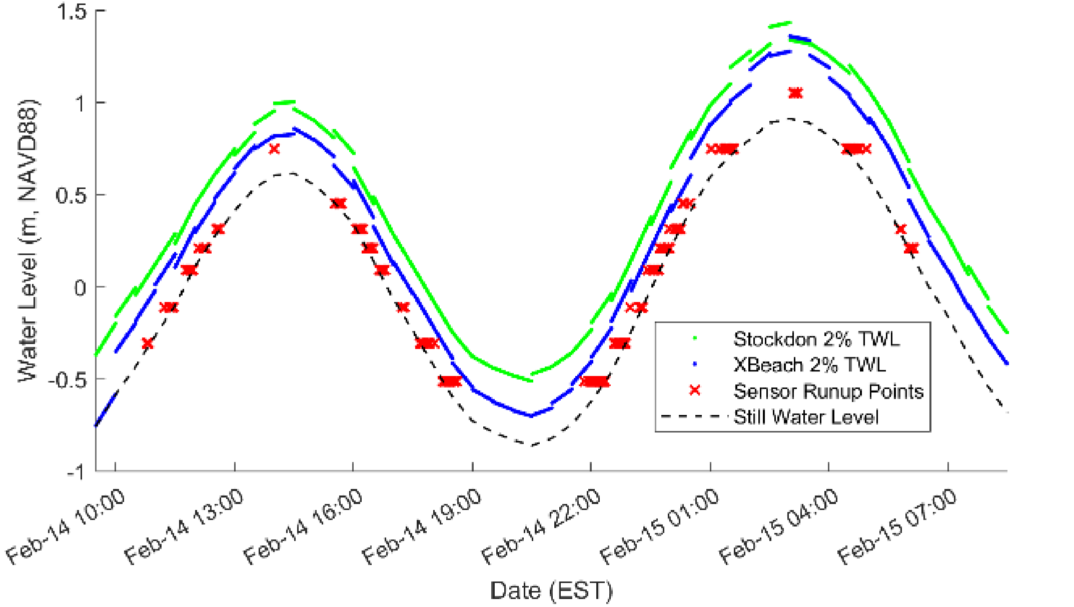




XBeach vs Field Results

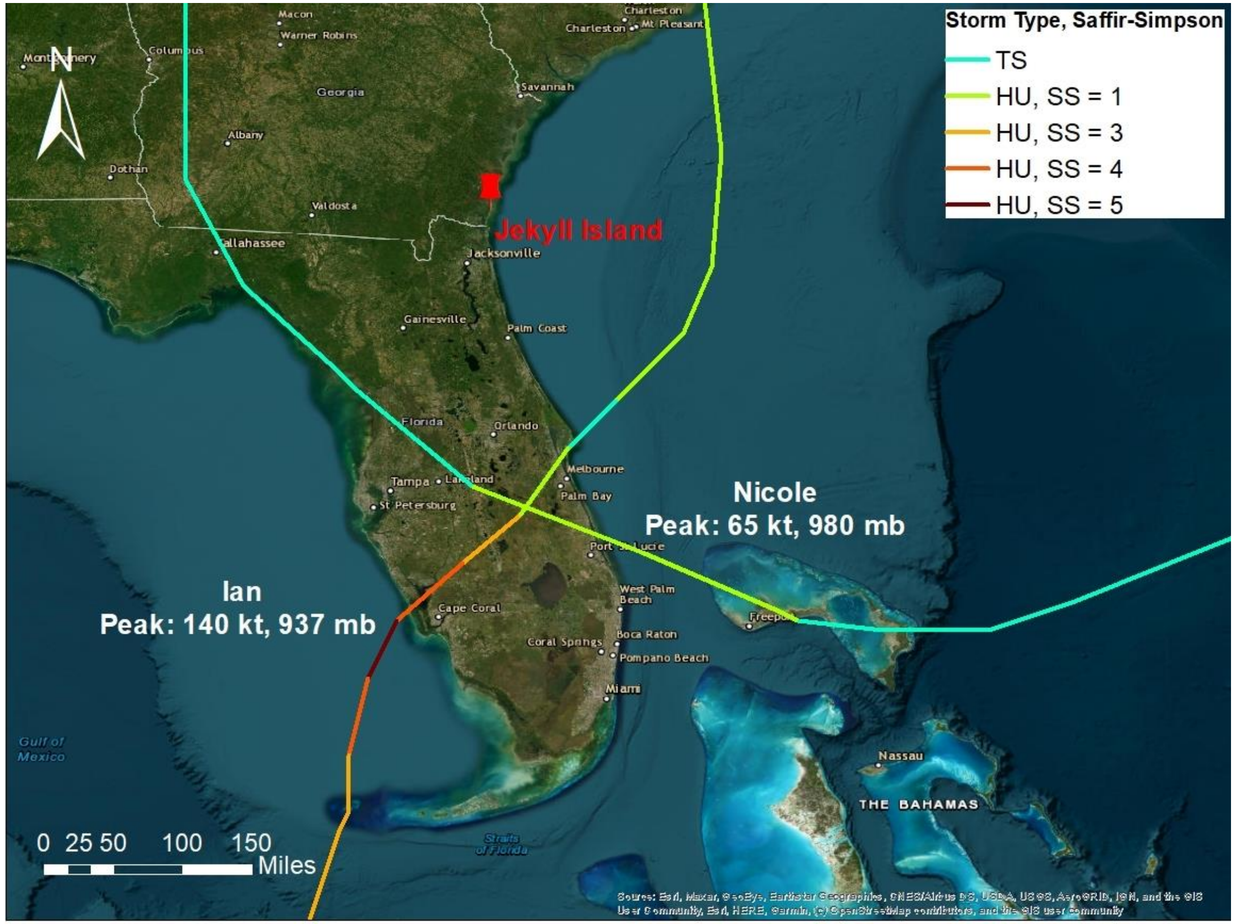
- Each observed runup point is achieved in the XBeach simulation without surpassing the next highest sensor
- Stockdon 2006 method tends to produce higher runup values with this site
  - RMS difference of 16 cm
    - Can range from about 30-64% of the total runup
- Beach slope: 0.031
- Wave Heights: 0.3 – 0.5 m
- Wave Periods: 8 – 11 s
  - Data in 30-min intervals



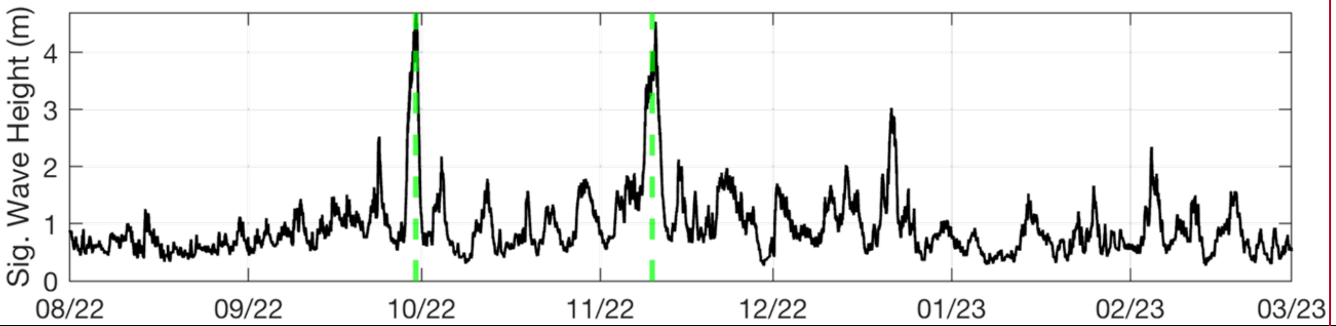


Trial Runs

- Hurricanes Ian and Nicole
  - Sep and Nov of 2022
  - Impacts to Georgia Coast

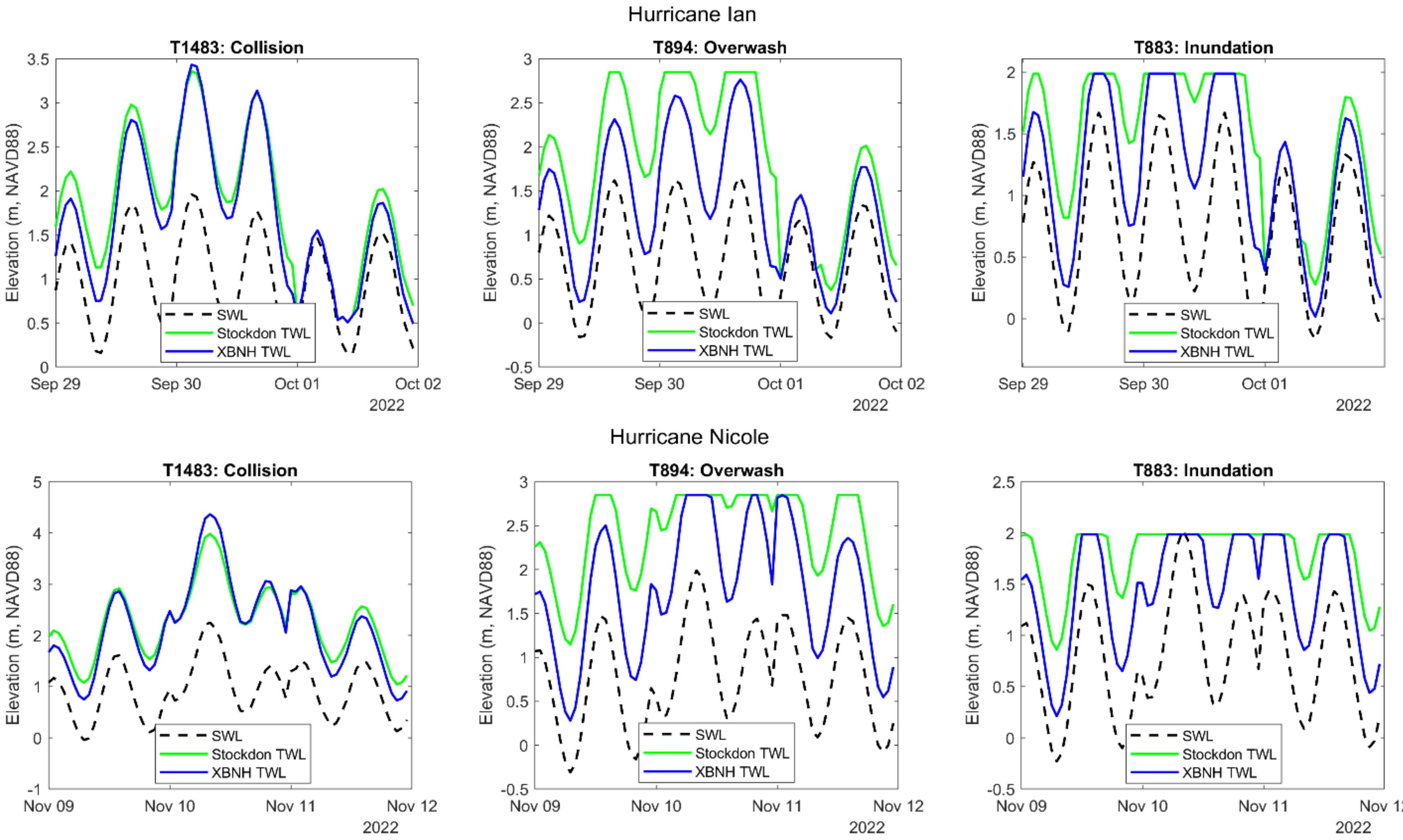


- Tide and wave inputs provided by the USGS TWLCC Viewer API

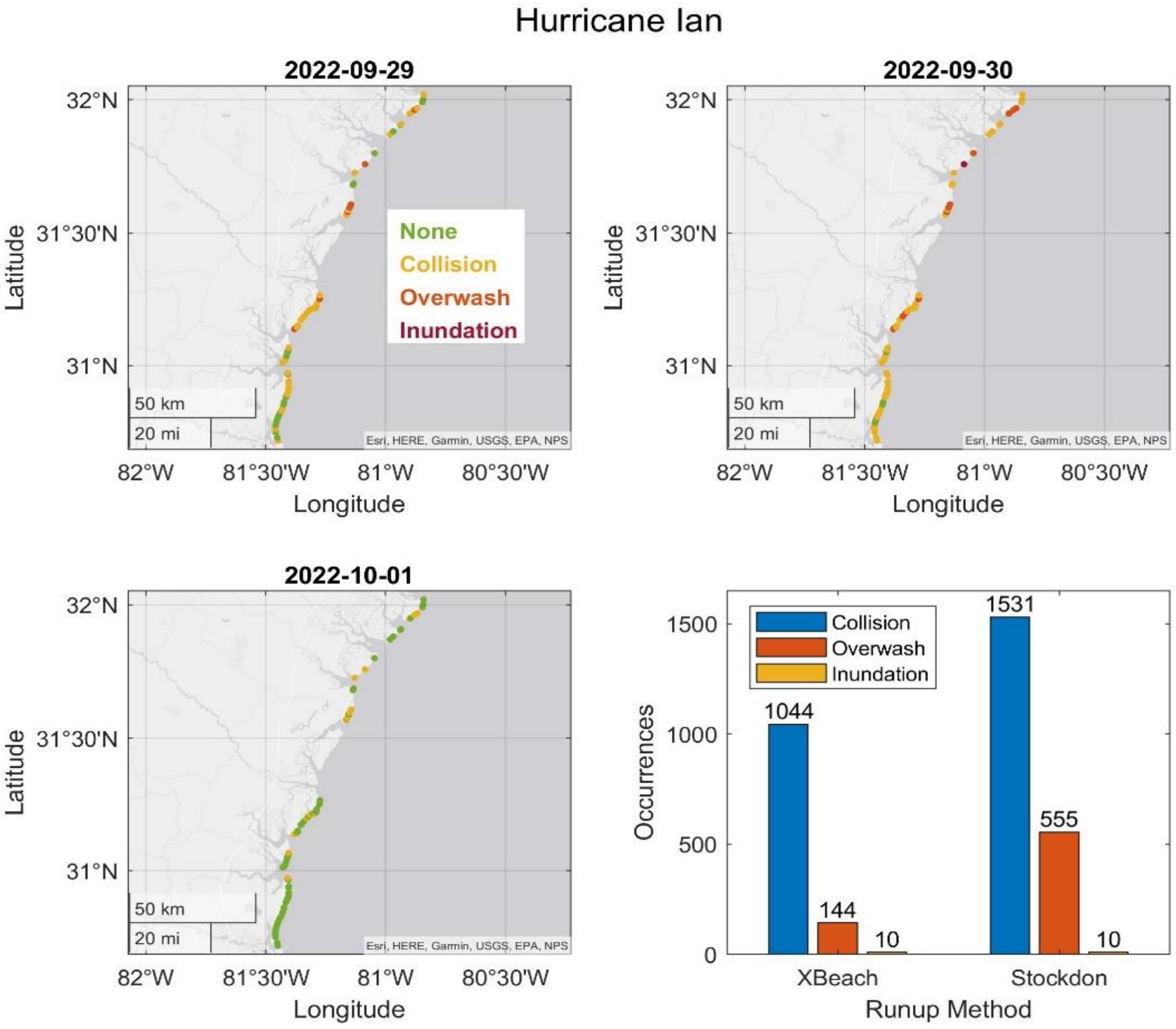


Trial Results

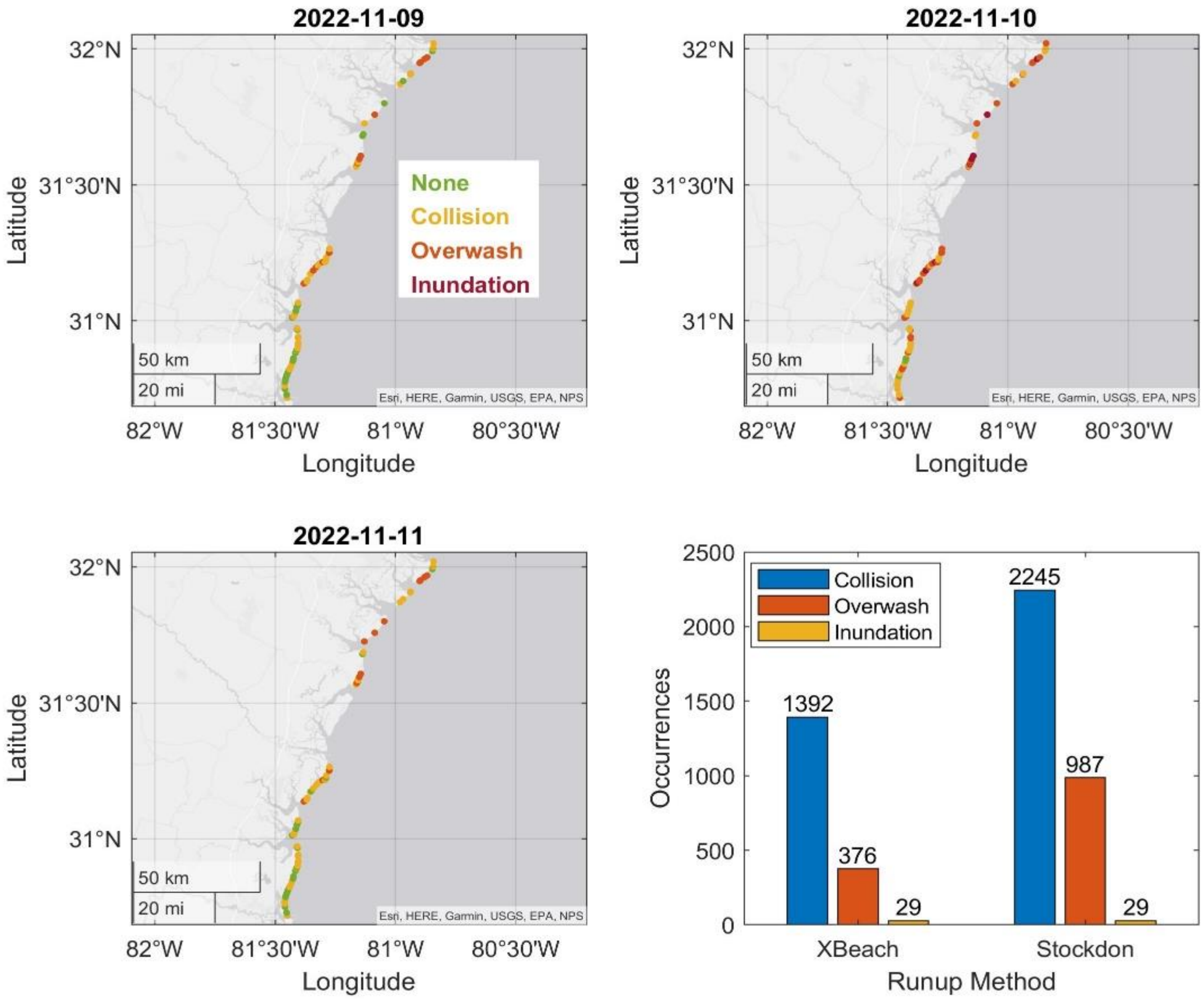
- Ian peak wave conditions:
  - H_s = 5.0 m, T_P = 10.1 s
- Nicole peak wave conditions:
  - H_s = 5.9 m, T_P = 11.8 s



Transect ID	Latitude	Longitude	Dune Crest (m)	Beach Slope	Ian Max Impact	TWL RMS Difference (m)	Nicole Max Impact	TWL RMS Difference (m)
883	31.581	-81.157	1.99	0.039	Inundation	0.39	Inundation	0.45
894	31.801	-81.047	2.85	0.064	Overwash	0.58	Overwash	0.70
1483	30.748	-81.459	4.59	0.027	Collision	0.20	Collision	0.22


Hurricane Ian
2022-09-29
2022-09-30
2022-10-01
32°N
31°30'N
31°N
Latitude
82°W
81°30'W
81°W
80°30'W
Longitude
None
Collision
Overwash
Inundation
50 km
20 mi
Esri, HERE, Garmin, USGS, EPA, NPS
Collision
Overwash
Inundation
Occurrences
0
500
1000
1500
1044
144
10
1531
555
10
XBeach
Stockdon
Runup Method

Hurricane Nicole



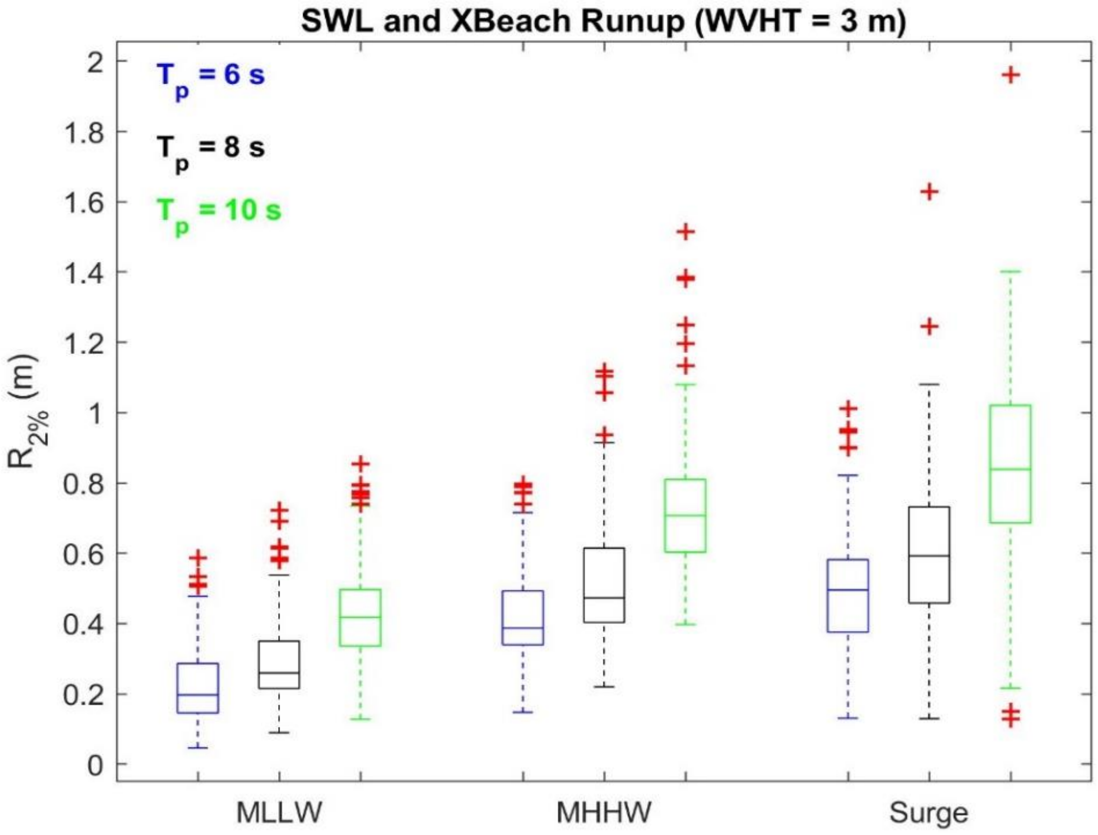
Discussion – Jekyll Island Runup Experiment

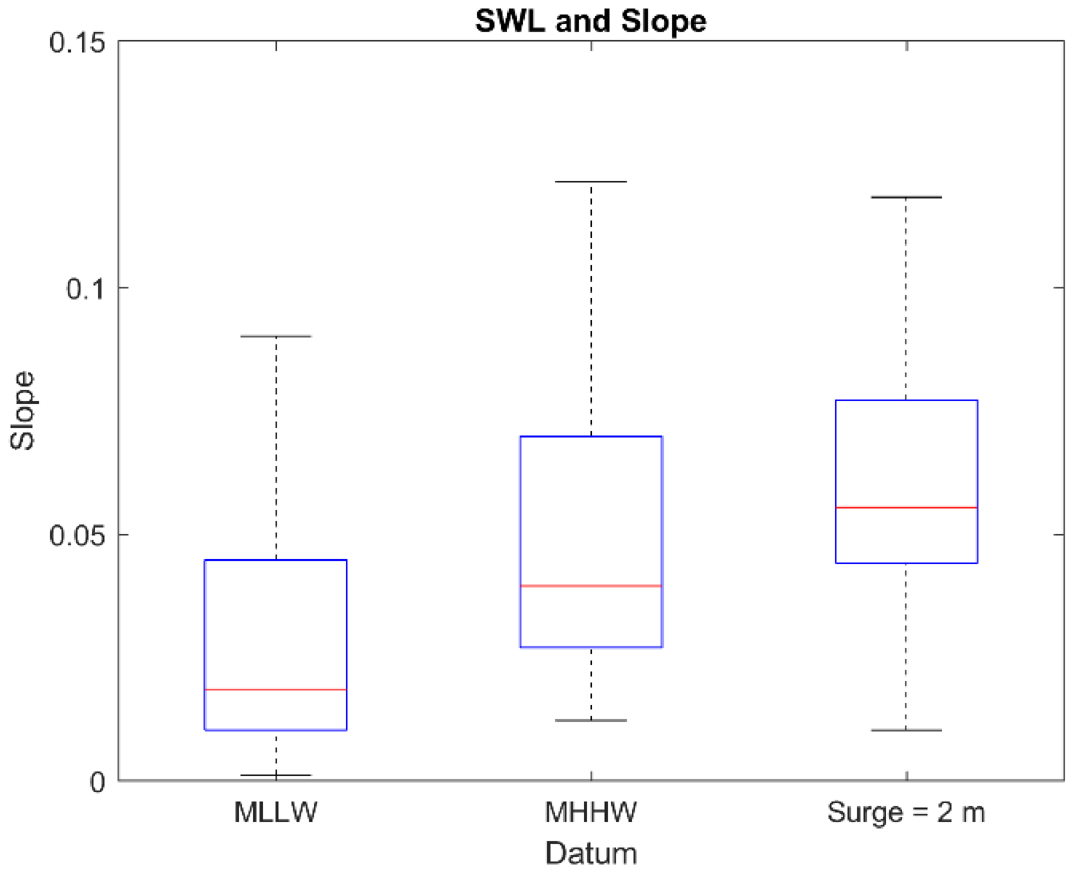
- This field experiment found XBNH to effectively simulate wave runup for the fair-weather wave conditions
  - Adjust methods to replicate under stronger wave conditions
- The benefits of this method include a temporally continuous data set even through the night
- Filtering out noise and calibrating the results to accurately capture runup events is the most extensive part of the post-processing, but works effectively
- For the location and conditions, the experiment suggests the XBNH results more closely resembled the observed results than the Stockdon (2006) method

Discussion – Forecasting Evaluation

- This model effectively predicted scenarios of collision, overwash, and inundation on the Georgia Coast from Hurricanes Ian and Nicole
- On a more detailed level, it also provided the XBNH-derived TWL and wave runup for each site for every hour
- Using the Stockdon 2006 method significantly increases the amount of collision and overwash throughout the hourly forecasts
- Our findings also establish that wave runup in XBNH is significantly tied to the still water level
  - This trend can likely be explained, in part, by the general shapes of beaches and dunes. Slopes tend to be lower at the MLLW for these profiles and increase as the dune is approached, peaking at some point on the dune (surge level).
  - These findings emphasize the importance of considering the still water level when modeling wave runup in XBeach.

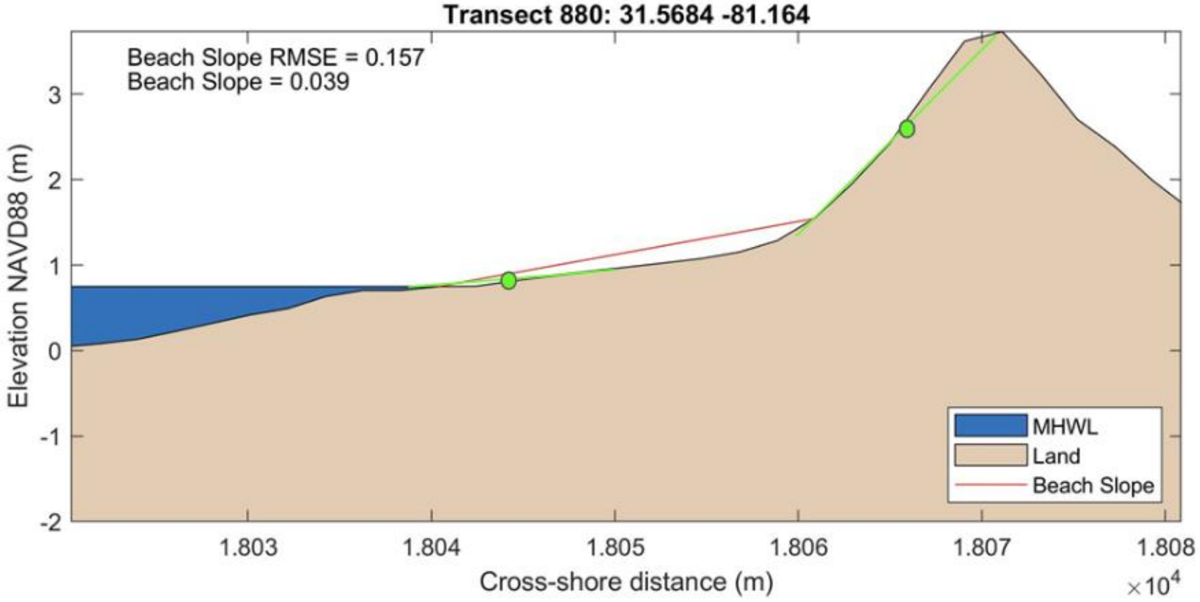
Sensitivity of Runup to the Stillwater Level

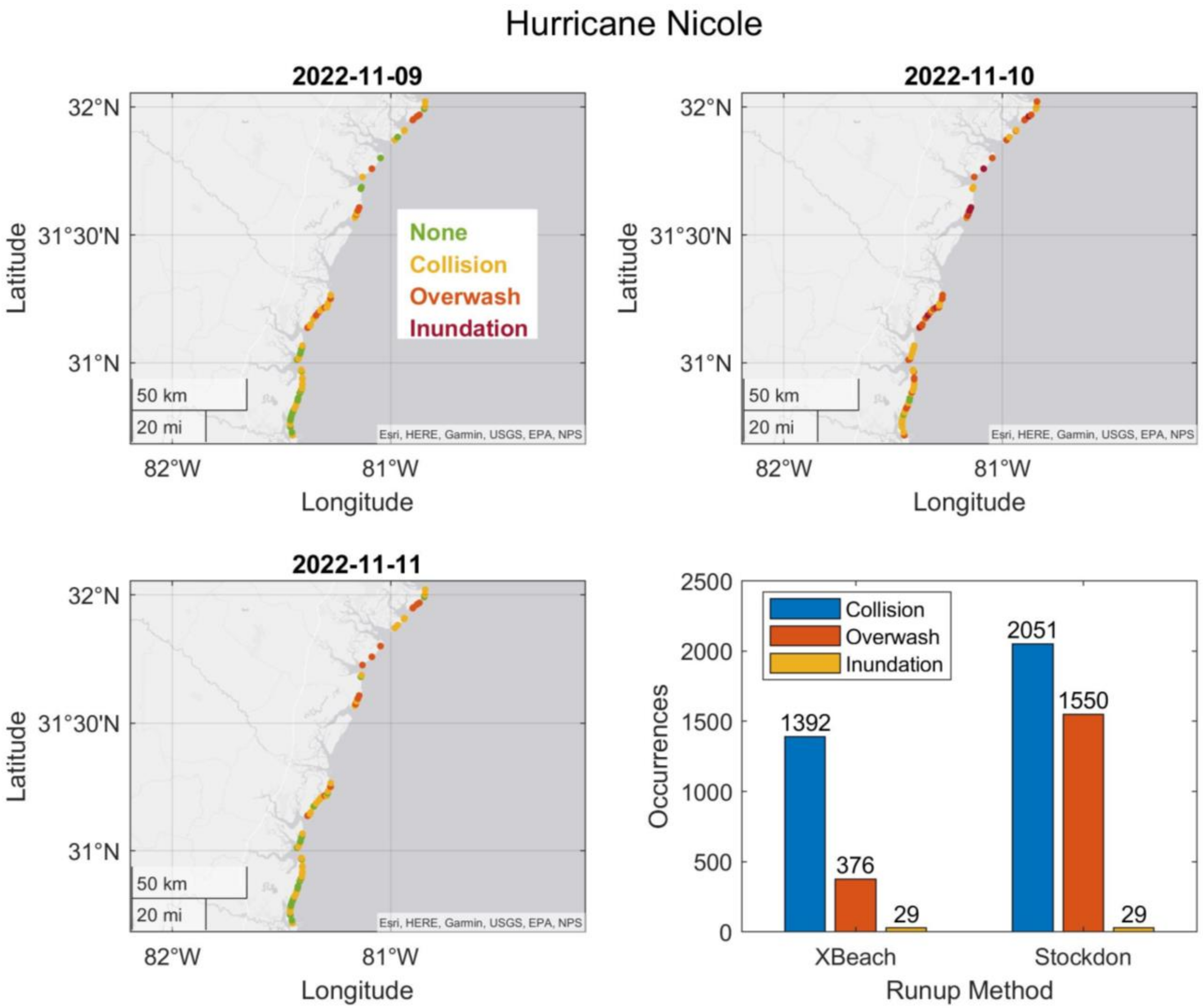




Alternative "Active Slope" Method

Originally; 2245 Collision, 987 Overwash for Hurricane Nicole





Limitations and Future Work

- Fairweather wave conditions for the field experiment
- More validation should be conducted before implementing this method for decision-making and public safety
- This is limited to the most recently updated topo-bathy available, and continuous updates are necessary to ensure that the results are as accurate as possible.
    - Having detailed topo-bathy of the beaches' equilibrium profiles would allow the model to simulate storm impacts on the beaches' recovered state, possibly requiring fewer updates
- This method does not account for changes in morphology throughout the forecast because of the non-hydrostatic model
- Future work can also expand this model beyond the coast of Georgia and for the full range of the Mickey and Passeri (2023) dataset (East Coast and Gulf of Mexico)

Conclusions

- Forecasting wave runup and total water levels on a regional scale provides important insight into coastal hazards and beach conditions
- Our XBNH-derived method forecasts hourly total water levels for 81 different locations and predicted impacts of collision, overwash, and inundation for Hurricanes Ian and Nicole in just minutes.
    - (~8 min to retrieve API data, ~1 second to make calculations)
- The method aims at reducing site bias and limitations introduced when using an empirical model formed by available datasets of runup observations
- Throughout the study, using the Stockdon et al. (2006) empirical method for each site usually produced a higher runup value and increased instances of collision and overwash for our sites, especially in storm conditions for Hurricanes Ian and Nicole of 2022.
- Runup in XBNH is substantially tied to the still water level, as runup tends to increase from MLLW, MHHW, and a 2 m datum, respectively. It is important to account for this in simulations.

Acknowledgements

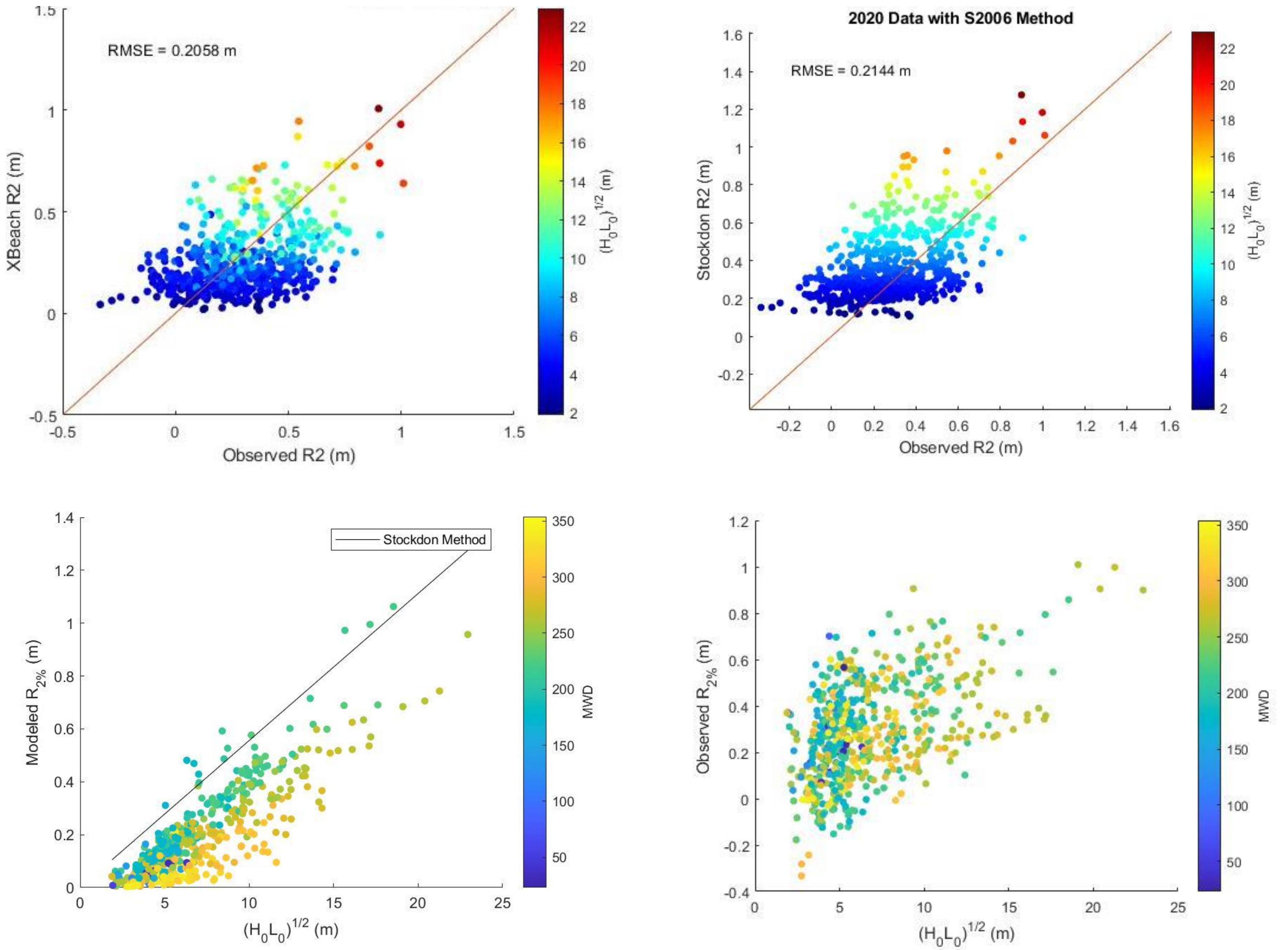
This work was made possible by the US Department of Interior – USGS / Cooperative Ecosystem Studies Unit, Gulf Coast CESU / Project Award: G20AS00137.

Contact: mbilskie@uga.edu
@DrMattVBilskie

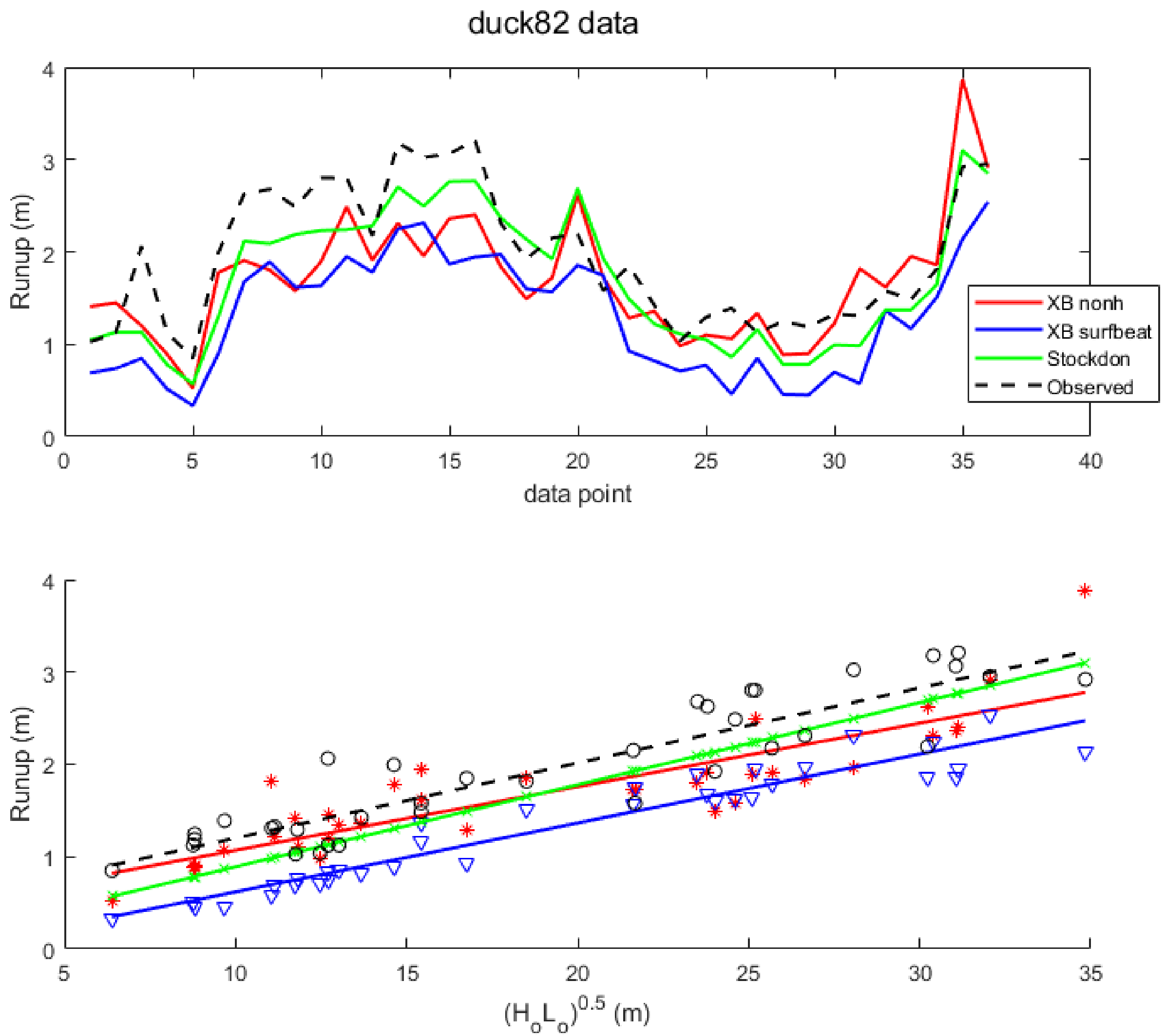
https://coast.engr.uga.edu/

Fiegelist, R., Bilskie, M.V., Passeri, D.L., Woodson, C.B., “A Process-Based Model for Forecasting Wave Runup along the Coast of Georgia,” *Coastal Engineering*. Under Review.

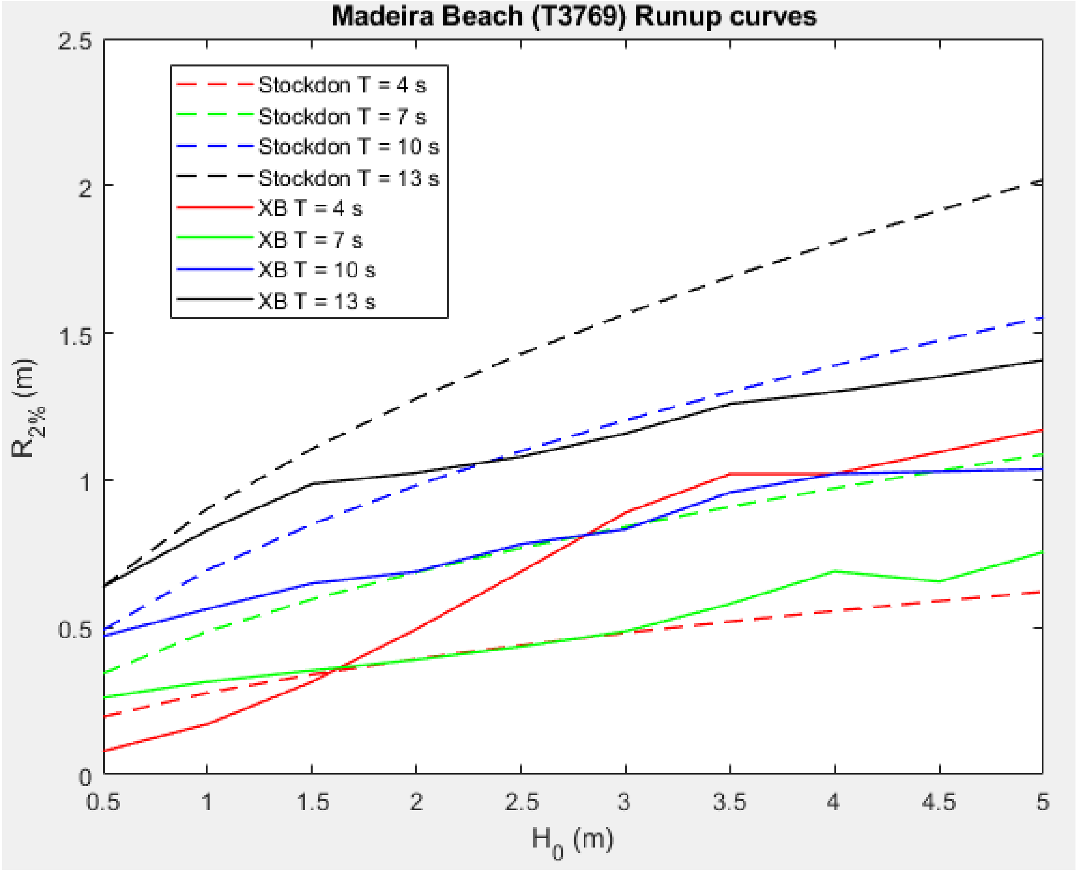
Bonus 1


RMSE = 0.2058 m
XBeach R2 (m)
Observed R2 (m)
$(H_0L_0)^{1/2}$ (m)
2020 Data with S2006 Method
RMSE = 0.2144 m
Stockdon R2 (m)
Observed R2 (m)
$(H_0L_0)^{1/2}$ (m)
Stockdon Method
Modeled $R_{2\%}$ (m)
$(H_0L_0)^{1/2}$ (m)
MWD
Observed $R_{2\%}$ (m)
$(H_0L_0)^{1/2}$ (m)
MWD

Bonus 2



duck82 data
Runup (m)
data point
XB nonh
XB surfbeat
Stockdon
Observed
Runup (m)
$(H_oL_o)^{0.5}$ (m)



Madeira Beach (T3769) Runup curves
Stockdon T = 4 s
Stockdon T = 7 s
Stockdon T = 10 s
Stockdon T = 13 s
XB T = 4 s
XB T = 7 s
XB T = 10 s
XB T = 13 s
$R_{2\%}$ (m)
H_0 (m)

References

- Asbury H. Sallenger, Jr. (2000). Storm Impact Scale for Barrier Islands. *Journal of Coastal Research*, *16*(3), 890–895.
- Beuzen, T., Goldstein, E. B., & Splinter, K. D. (2019). Ensemble models from machine learning: An example of wave runup and coastal dune erosion. *Natural Hazards and Earth System Sciences*, *19*(10), 2295–2309. https://doi.org/10.5194/nhess-19-2295-2019
- Cariolet, J.-M., & Suanez, S. (2013). Runup estimations on a macrotidal sandy beach. *Coastal Engineering*, *74*, 11–18. https://doi.org/10.1016/j.coastaleng.2012.11.008
- Cohn, N., & Ruggiero, P. (2016). The influence of seasonal to interannual nearshore profile variability on extreme water levels: Modeling wave runup on dissipative beaches. *Coastal Engineering*, *115*, 79–92. https://doi.org/10.1016/j.coastaleng.2016.01.006
- Cohn, N., Ruggiero, P., Ortiz, J., & Walstra, D. J. (2014). Investigating the role of complex sandbar morphology on nearshore hydrodynamics. *Journal of Coastal Research*, *70*(sp1), 53–58. https://doi.org/10.2112/SI65-010.1
- Dodet, G., Leckler, F., Sous, D., Ardhuin, F., Filipot, J. f., & Suanez, S. (2018). Wave Runup Over Steep Rocky Cliffs. *Journal of Geophysical Research: Oceans*, *123*(10), 7185–7205. https://doi.org/10.1029/2018JC013967
- Doran, K. J., Long, J. W., Birchler, J. J., Brenner, O. T., Hardy, M. W., Morgan, K. L. M., Stockdon, H. F., & Torres, M. L. (2017). *Lidar-derived Beach Morphology (Dune Crest, Dune Toe, and Shoreline) for U.S. Sandy Coastlines* [Data set]. U.S. Geological Survey. https://doi.org/10.5066/F7GF0S0Z
- Fiedler, J. W., Brodie, K. L., McNinch, J. E., & Guza, R. T. (2015). Observations of runup and energy flux on a low-slope beach with high-energy, long-period ocean swell. *Geophysical Research Letters*, *42*(22), 9933–9941. https://doi.org/10.1002/2015GL066124
- Guedes, R. M. C., Bryan, K. R., Coco, G., & Holman, R. A. (2011). The effects of tides on swash statistics on an intermediate beach. *Journal of Geophysical Research: Oceans*, *116*(C4). https://doi.org/10.1029/2010JC006660
- Holland, K. T., Raubenheimer, B., Guza, R. T., & Holman, R. A. (1995). Runup kinematics on a natural beach. *Journal of Geophysical Research*, *100*(C3), 4985. https://doi.org/10.1029/94JC02664
- Holman, R. A., & Guza, R. T. (1984). Measuring run-up on a natural beach. *Coastal Engineering*, *8*(2), 129–140. https://doi.org/10.1016/0378-3839(84)90008-5
- Lashley, C. H., Zanuttigh, B., Bricker, J. D., van der Meer, J., Altomare, C., Suzuki, T., Roeber, V., & Oosterlo, P. (2020). Benchmarking of numerical models for wave overtopping at dikes with shallow mildly sloping foreshores: Accuracy versus speed. *Environmental Modelling & Software*, *130*, 104740. https://doi.org/10.1016/j.envsoft.2020.104740

References

- McCall, R. T., Masselink, G., Poate, T. G., Roelvink, J. A., Almeida, L. P., Davidson, M., & Russell, P. E. (2014). Modelling storm hydrodynamics on gravel beaches with XBeach-G. *Coastal Engineering*, *91*, 231–250. https://doi.org/10.1016/j.coastaleng.2014.06.007
- Mickey, R. C., Dalyander, P. S., McCall, R., & Passeri, D. L. (2020). Sensitivity of Storm Response to Antecedent Topography in the XBeach Model. *Journal of Marine Science and Engineering*, *8*(10), 829. https://doi.org/10.3390/jmse8100829
- Mickey, R. C., & Passeri, D. L. (2022). A Database of Topo-Bathy Cross-Shore Profiles and Characteristics for U.S. Atlantic and Gulf of Mexico Sandy Coastlines. *Data*, *7*(7), 92. https://doi.org/10.3390/data7070092
- Passarella, M., Goldstein, E. B., De Muro, S., & Coco, G. (2018). The use of genetic programming to develop a predictor of swash excursion on sandy beaches. *Natural Hazards and Earth System Sciences*, *18*(2), 599–611. https://doi.org/10.5194/nhess-18-599-2018
- Power, H. E., Gharabaghi, B., Bonakdari, H., Robertson, B., Atkinson, A. L., & Baldock, T. E. (2019). Prediction of wave runup on beaches using Gene-Expression Programming and empirical relationships. *Coastal Engineering*, *144*, 47–61. https://doi.org/10.1016/j.coastaleng.2018.10.006
- Quataert, E., Storlazzi, C., van Dongeren, A., & McCall, R. (2020). The importance of explicitly modelling sea-swell waves for runup on reef-lined coasts. *Coastal Engineering*,*160*, 103704. https://doi.org/10.1016/j.coastaleng.2020.103704
- Roelvink, D., McCall, R., Mehvar, S., Nederhoff, K., & Dastgheib, A. (2018). Improving predictions of swash dynamics in XBeach: The role of groupiness and incident-band runup. *Coastal Engineering*, *134*, 103–123. https://doi.org/10.1016/j.coastaleng.2017.07.004
- Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., & Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, *56*(11–12), 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006
- Ruggiero, P., Holman, R. A., & Beach, R. A. (2004). Wave run-up on a high-energy dissipative beach. *Journal of Geophysical Research: Oceans*, *109*(C6). https://doi.org/10.1029/2003JC002160
- Stockdon, H. F., Holman, R. A., Howd, P. A., & Sallenger, A. H. (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, *53*(7), 573–588. https://doi.org/10.1016/j.coastaleng.2005.12.005
- Stockdon, H. F., Long, J. W., Palmsten, M. L., Van der Westhuysen, A., Doran, K. S., & Snell, R. J. (2023). Operational forecasts of wave-driven water levels and coastal hazards for US Gulf and Atlantic coasts. *Communications Earth & Environment*, *4*(1), Article 1. https://doi.org/10.1038/s43247-023-00817-2