Prediction of Small Bay Flooding through Tidal Inlet and by Wave Overtopping of Barrier Beach

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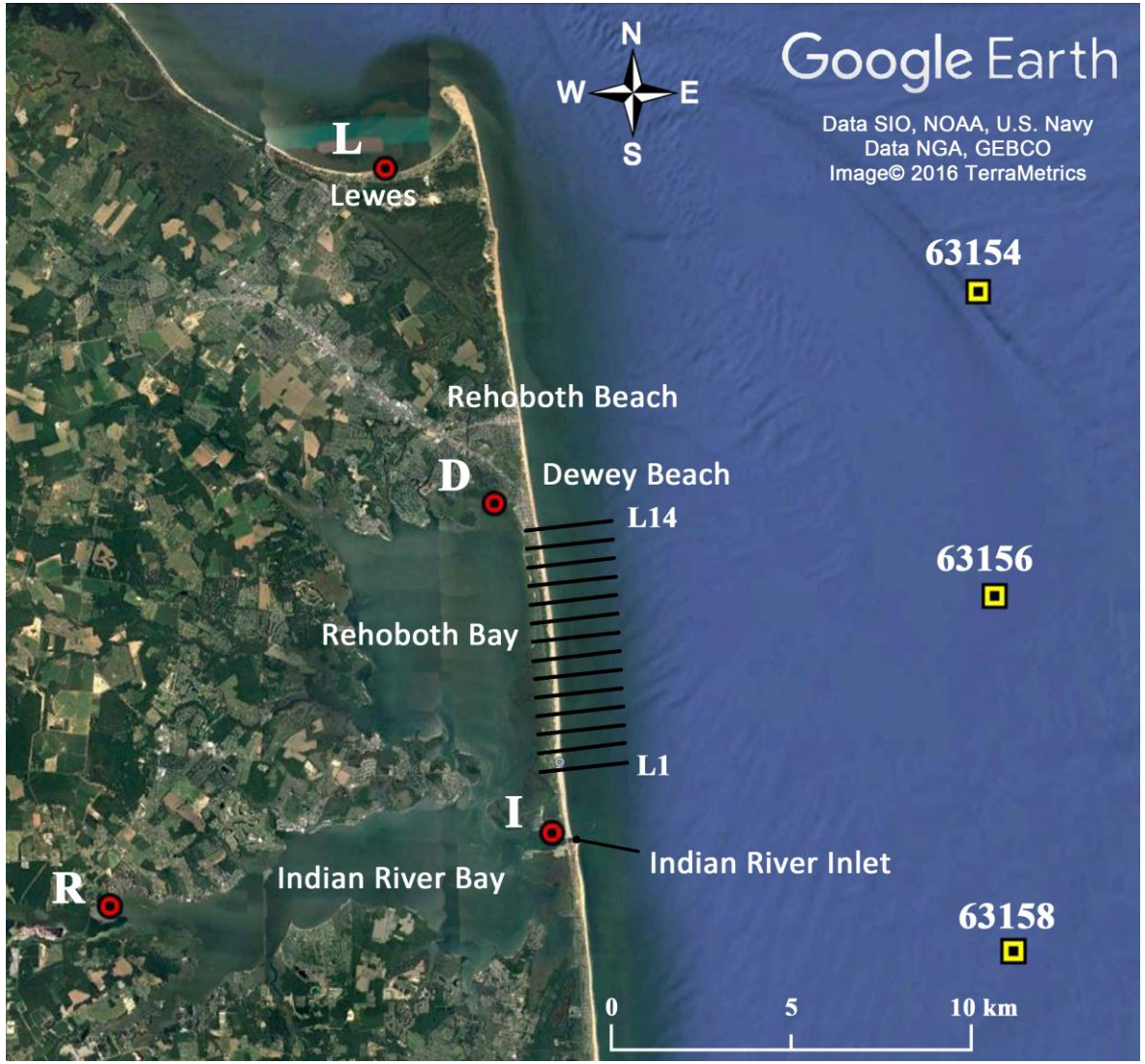
Introduction

- Simple analytical model to predict bay peak Stillwater elevations using available ocean Stillwater elevation data (94 years)
- Using field data with 27 storms during 2005-2015
- Coupled with cross-shore model CSHORE to predict wave overtopping of barrier beach during 2012 Hurricane Sandy
- Verified by additional 7 storms in 2016 and 2017

Available Field Data in Delaware



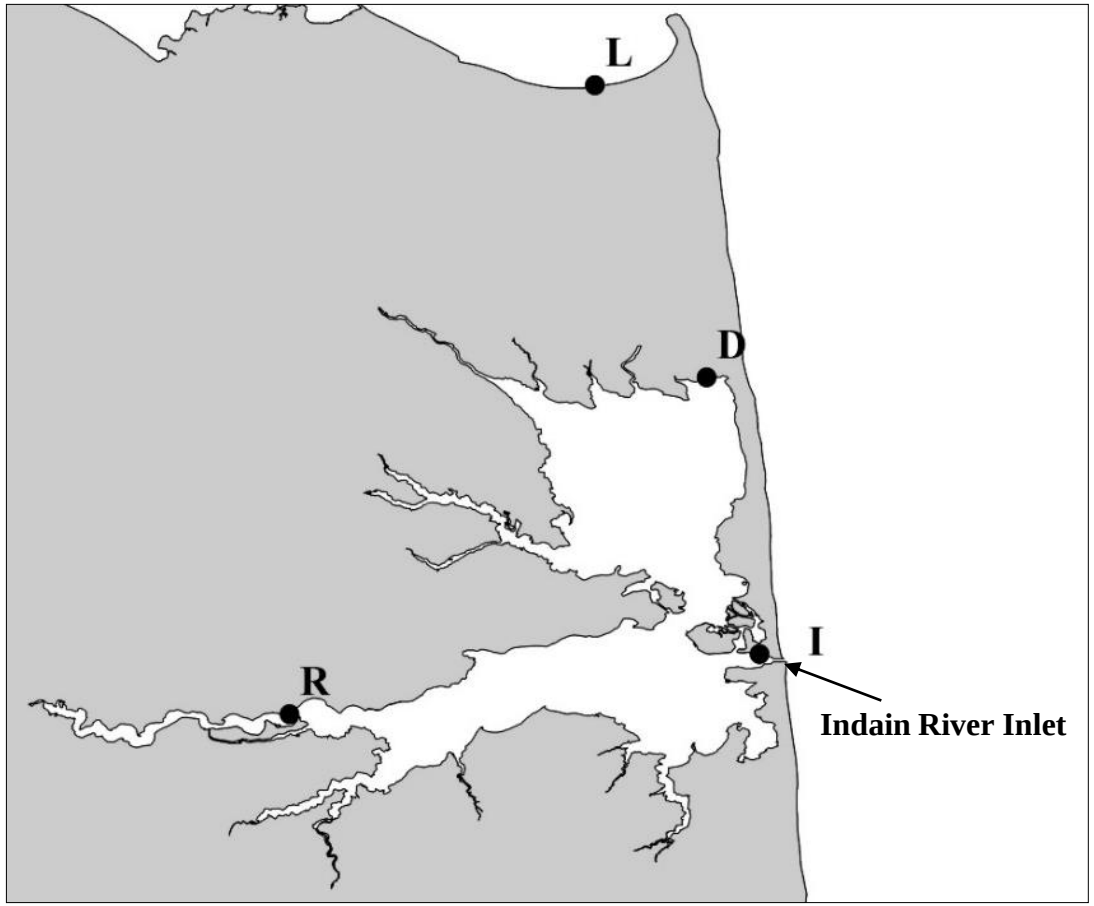
- **Tide gauges at**
  Lewes (L),
  Rehoboth Bay at Dewey Beach (D),
  Indian River Bay Inlet (I),
  Indian River at Rosedale Beach (R)

- **Wave data at WIS 631454, 63156, and 63158 stations**

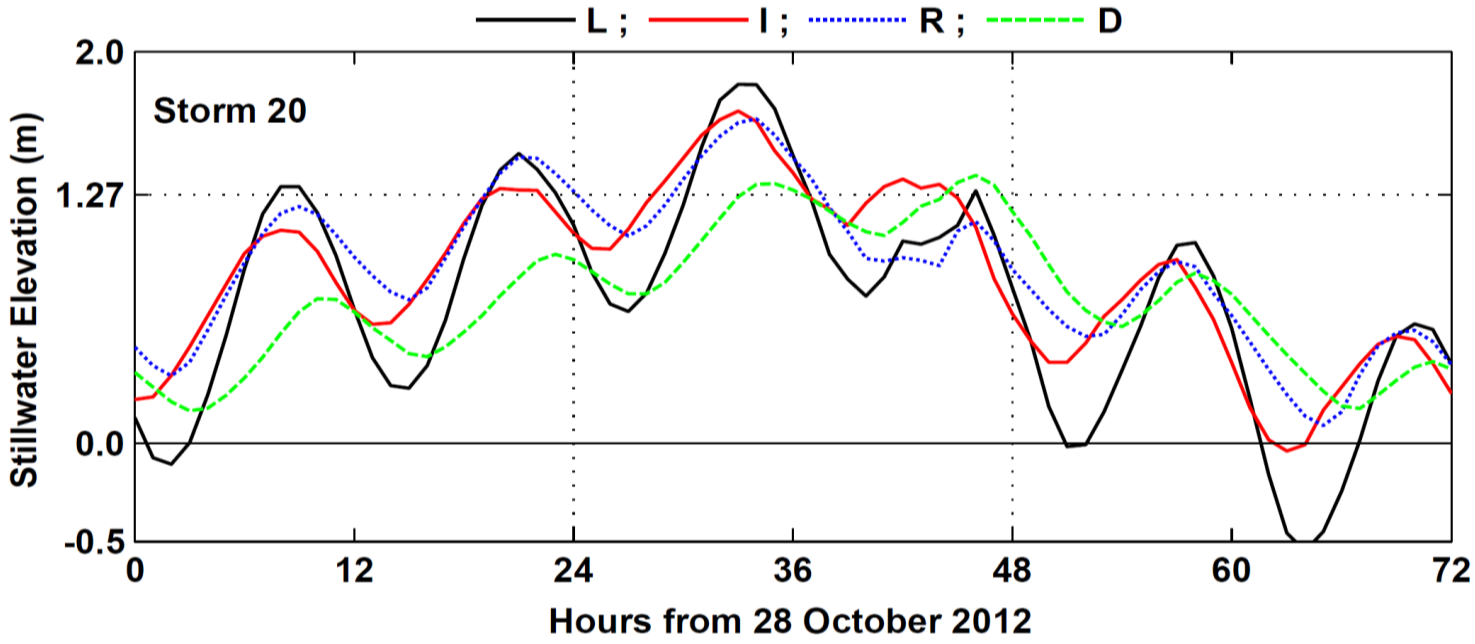
- **Barrier beach profile along 14 cross-shore lines (L1 to L14)**

Tide Gauge Data

- Datum = North American Vertical Datum of 1988 (NAVD88)
- Water level sampling rate = 0.1 h
- Bay tide gauge data (2005-2015) at I, R and D from U.S. Geological Survey (http://maps.waterdata.usgs.gov/)
- Ocean tide gauge data (94 yr) at Lewes (L) from National Oceanic and Atmospheric Administration (http://tidesandcurrents.noaa.gov/)
  - threshold peak stillwater elevation = 1.27m for storms (Nadal-Caraballo et al. 2016)



Tide Gauge Data



- 3-day time series of stillwater elevations at 4 tide gauges for storm 20
- Ocean storm tide at gauge L is reduced somewhat at Indian River Bay gauges I and R, and noticeably at Rehoboth Bay gauge D

Offshore Wave Data

- Wave Information Study Stations WIS 63154, 63156 and 63158 of U.S. Army Corps of Engineers (http://frf.usace.army.mil/cgi-bin/wis/)

- H_{mo} = spectral significant wave height,
  T_p = spectral peak period,
  θ = vector mean wave angle (Positive Clockwise)

- Differences of H_{mo} less than 10% at 3 stations → WIS63156 as numerical model input wave data

Beach Profile Data

- From Hurricane Sandy Digital Elevation Model of NOAA (http://tidesandcurrents.noaa.gov/)
- Beach profiles (cross-shore grid spacing = 8 m) for lines L1-L14 with 515-m alongshore spacing

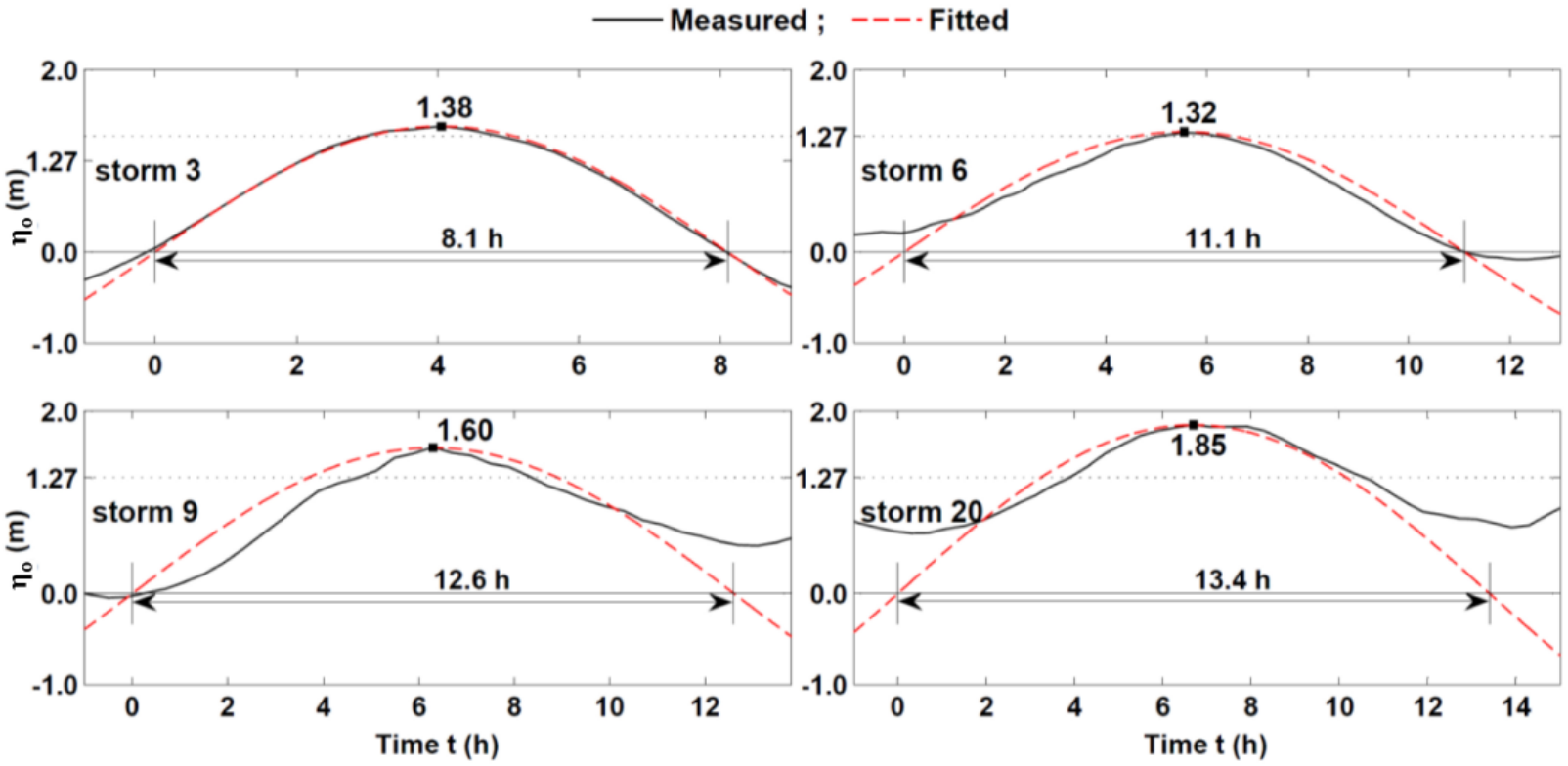
Analytical Model for Peak Stillwater Elevations

- Tidal hydraulics modeling (e.g., Dean and Dalrymple 2002) based on

  $\eta_o(t)$ = ocean stillwater elevation varying with time t; η_m = ocean peak stillwater elevation

  $\eta_B(t)$ = bay stillwater elevation (invariant horizontally); η_p = bay peak stillwater elevation

- Conservation of water volume in a small bay $A_B \frac{d\eta_B}{dt} = A_C U(t) + Q_W(t)$



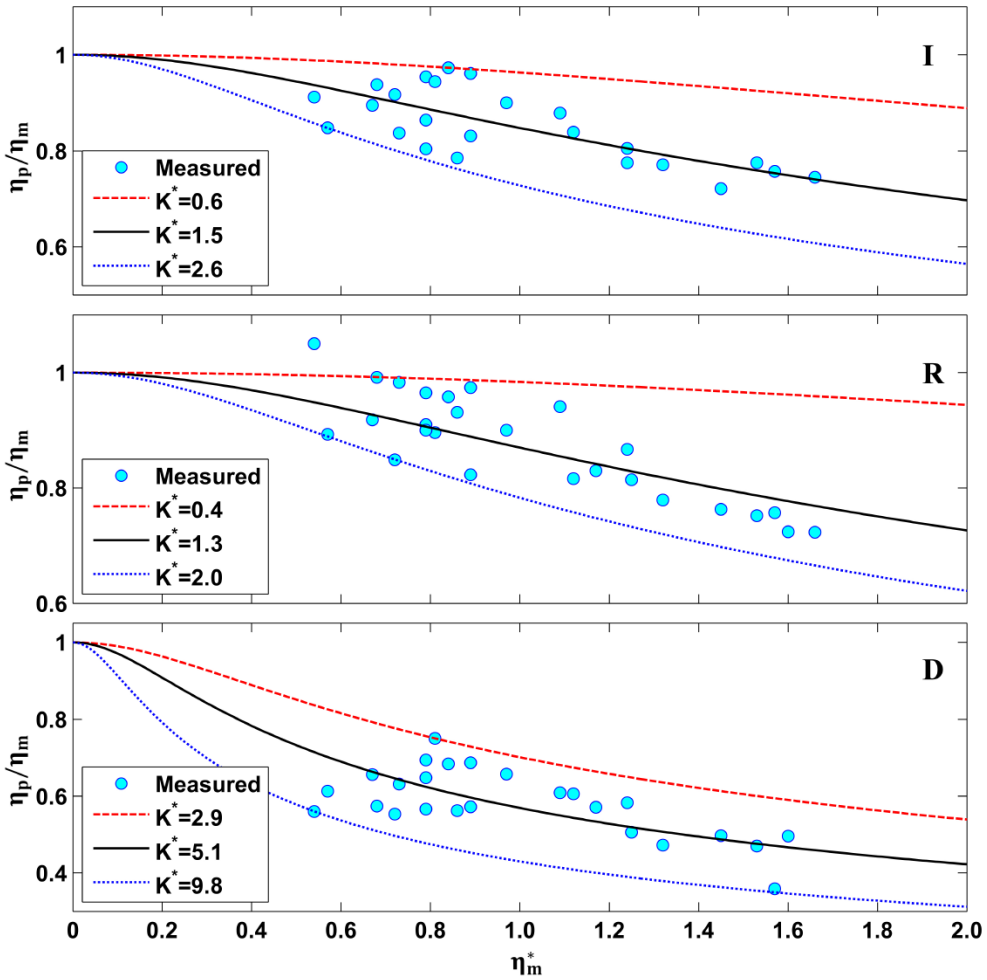
- **Measured and fitted temporal variations of ocean stillwater elevation $\eta_o(t)$ with its peak η_m at time $t = (T_s/2)$ for storms 3, 6, 9, and 20**

- Fitted: $\eta_o(t) = \eta_m sin\left(\frac{\pi t}{T_s}\right)$ for $0 \le t \le T_s$

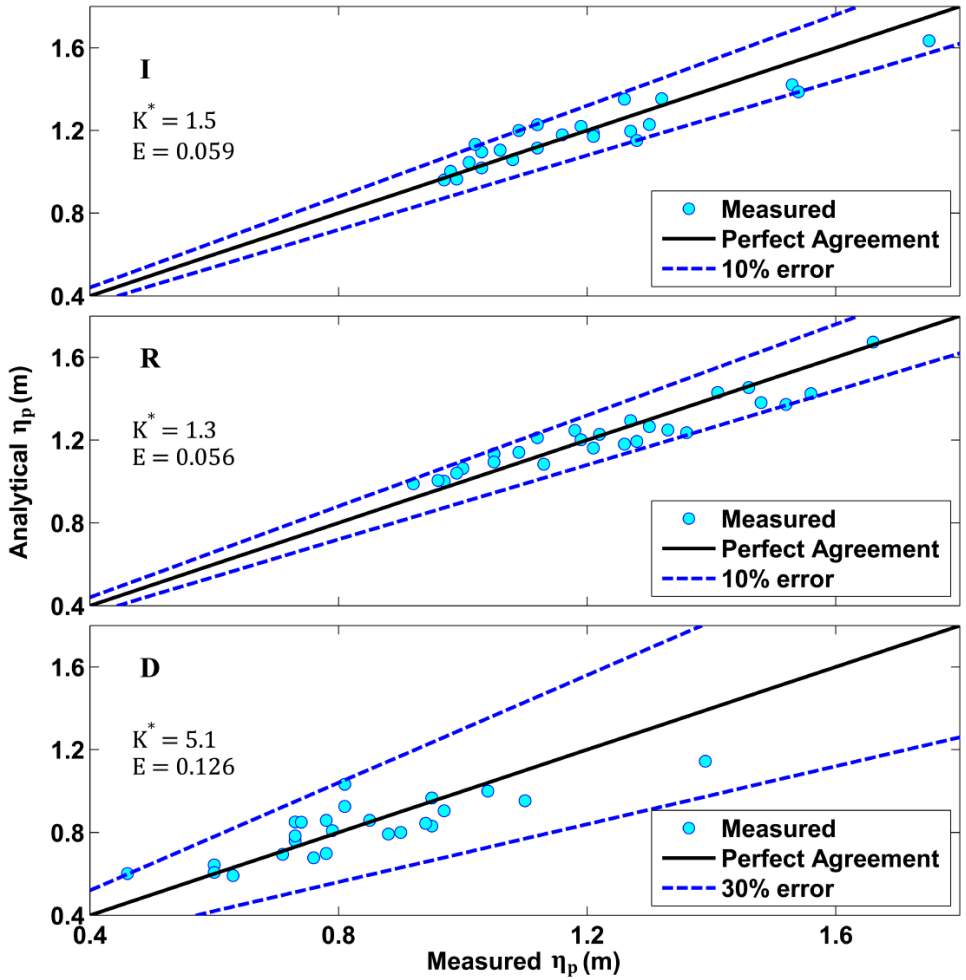
  T_s = surge duration

- **Inlet and bay parameter K^***
- **Surge steepness parameter η_m^***

$$K^* = \frac{8\pi K}{3}\left(\frac{A_B}{A_C}\right)^2 \times 10^{-10};\ \eta_m^* = \frac{\eta_m}{gT_s^2} \times 10^{10}$$



- Measured and analytical ratios (η_p/η_m) as a function of surge steepness parameter η_m^* for range of inlet and bay parameter K^* at tide gauges I, R, and D



- Measured and analytical peak elevations η_p in bay at tide gauges I ($K^* = 1.5$), R ($K^* = 1.3$), and D ($K^* = 5.1$) with 10% or 30% error range and root-mean-square relative error E

Wave Overtopping of Barrier Beach during Hurricane Sandy

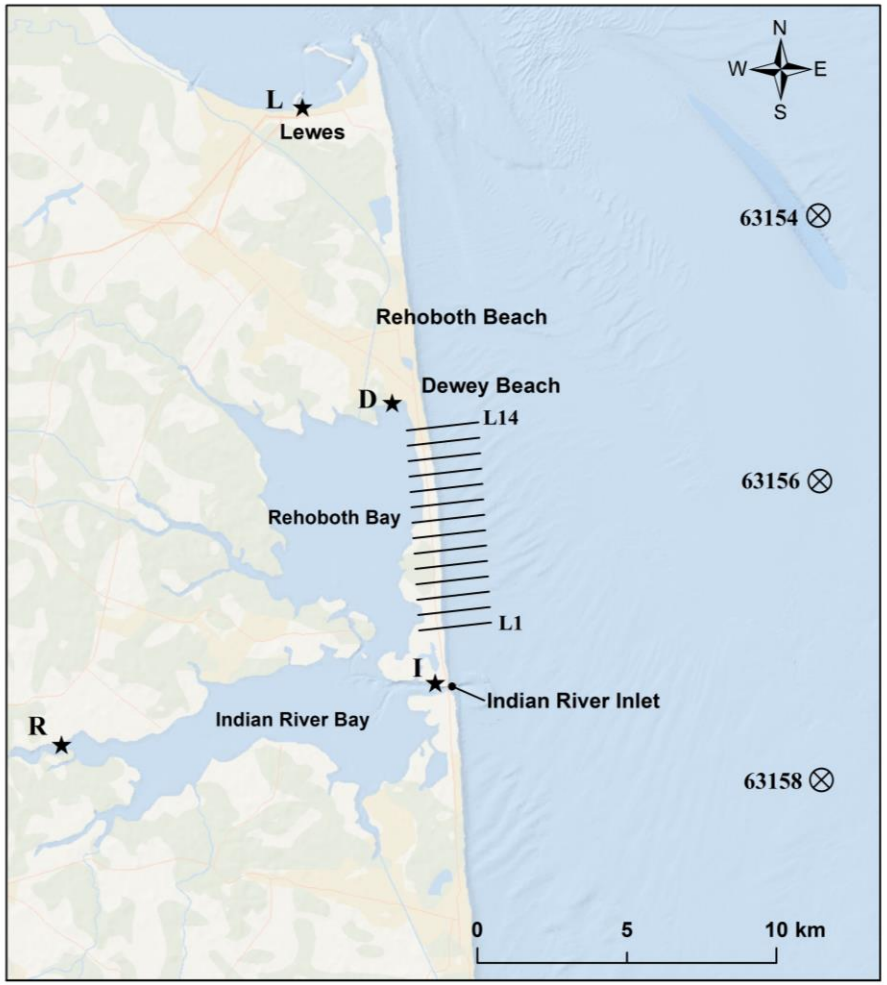

Indian River Inlet 10/30/2012

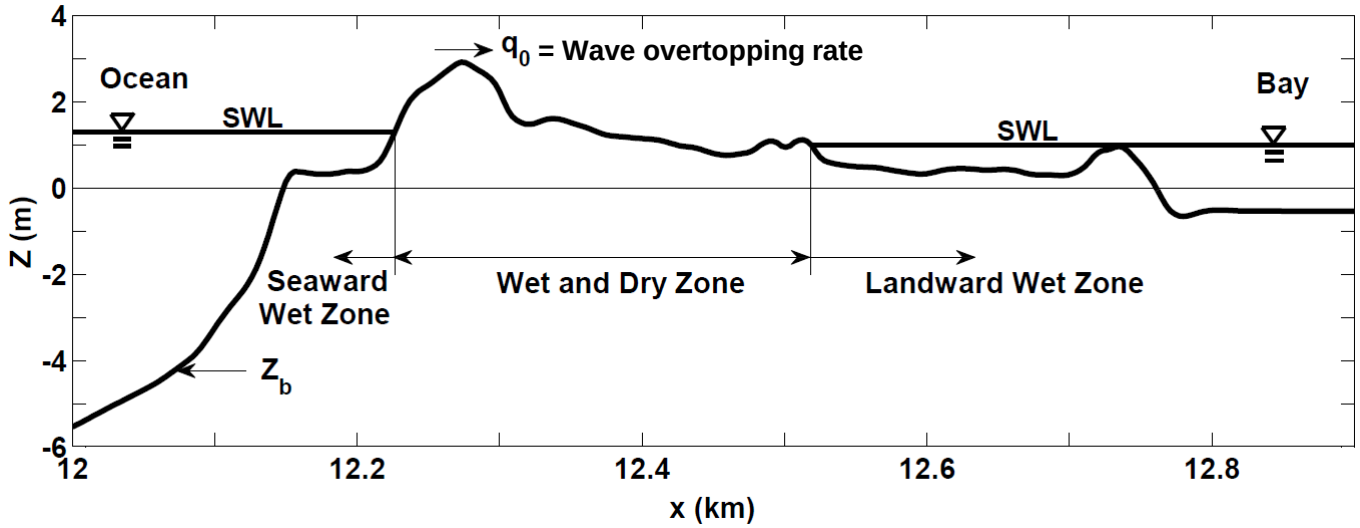

Rt 1 10/31/12


Rt 1 10/31/12

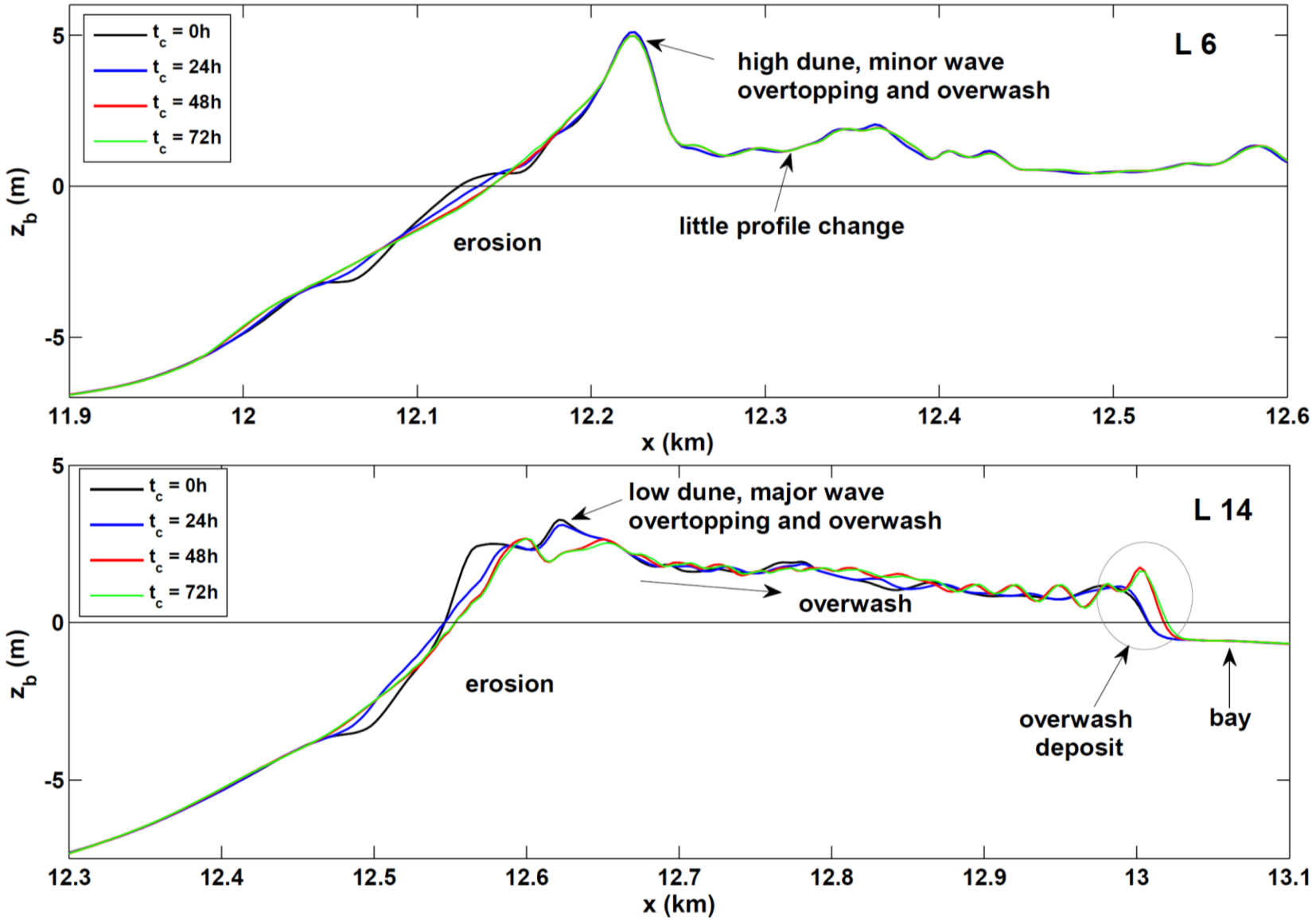
- Wave overwash deposit observed after Hurricane Sandy but no measurement of wave overtopping

The Cross-shore Model CSHORE



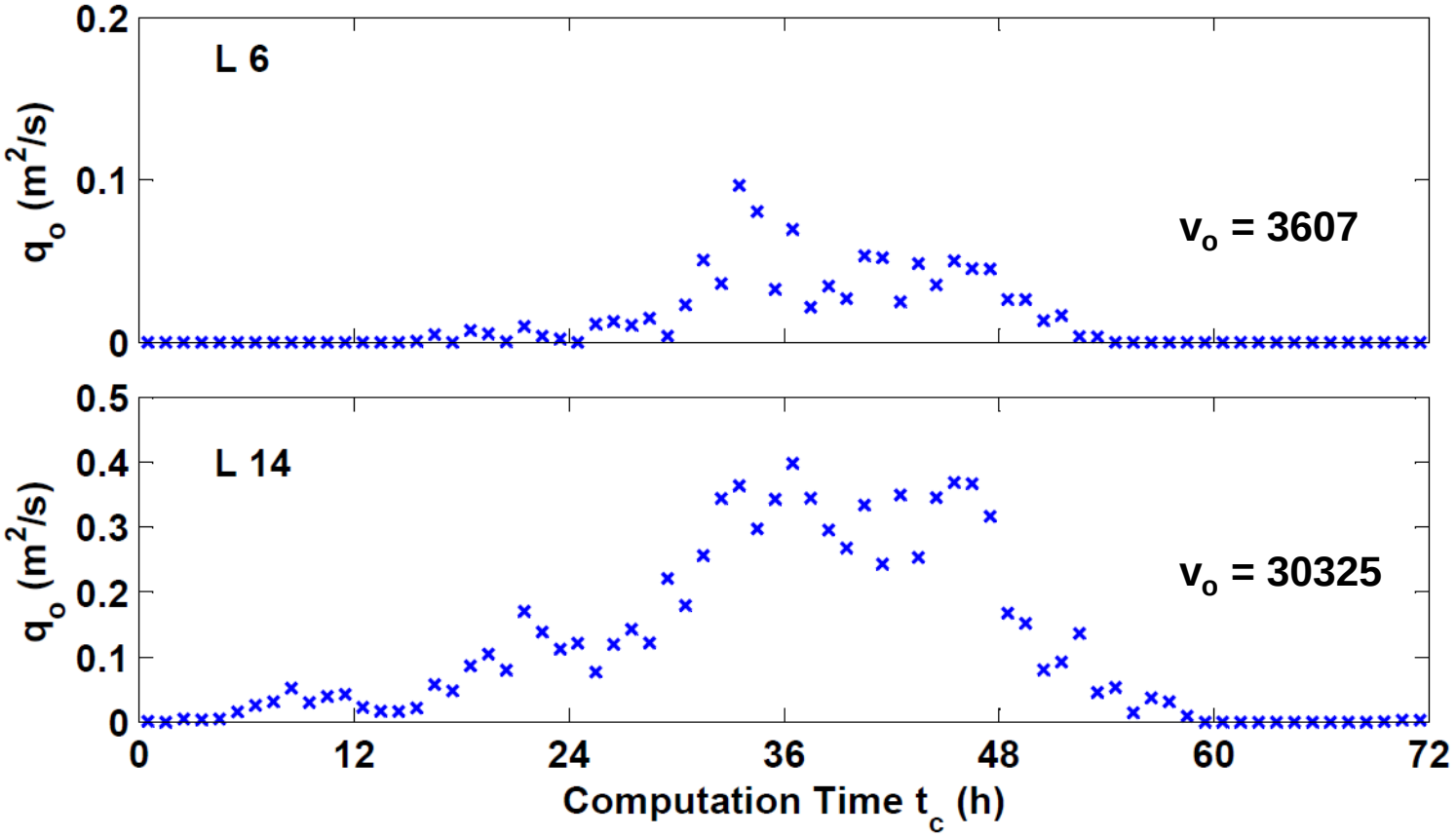


- Cross-shore model CSHORE was compared with beach erosion and recovery data along 14 cross-shore lines (spanning 5 km alongshore)
- 72-h computation for wave overtopping
- Barrier beach is assumed to consist of 0.33-mm sand without regard to vegetation and a paved road
- If lowered dune crest elevation becomes below ocean SWL, beach becomes submerged ➡ assumed: bay SWL = ocean SWL



- L6 = example of high dune crest
- L14 = example of low dune crest

- **Computed temporal variation of hourly wave overtopping rate q_o per unit width along cross-shore lines L6, and L14**



- Each line represents 515-m alongshore length
- Wave overtopping volume v_o (m^3/m) per unit width
- Total overtopping volume $V_o = 97 \times 10^6$ m^3 over 7.2-km barrier beach
- (V_o/A_B) = 1.3 m over bay surface $A_B = 75$ km^2

Analytical Model Including Wave Overtopping

- Conservation of water volume in a small bay

$$A_B \frac{d\eta_B}{dt} = A_C U(t) + Q_w(t)$$

- Assume $Q_w(t)$ and $\eta_o(t)$ are in phase

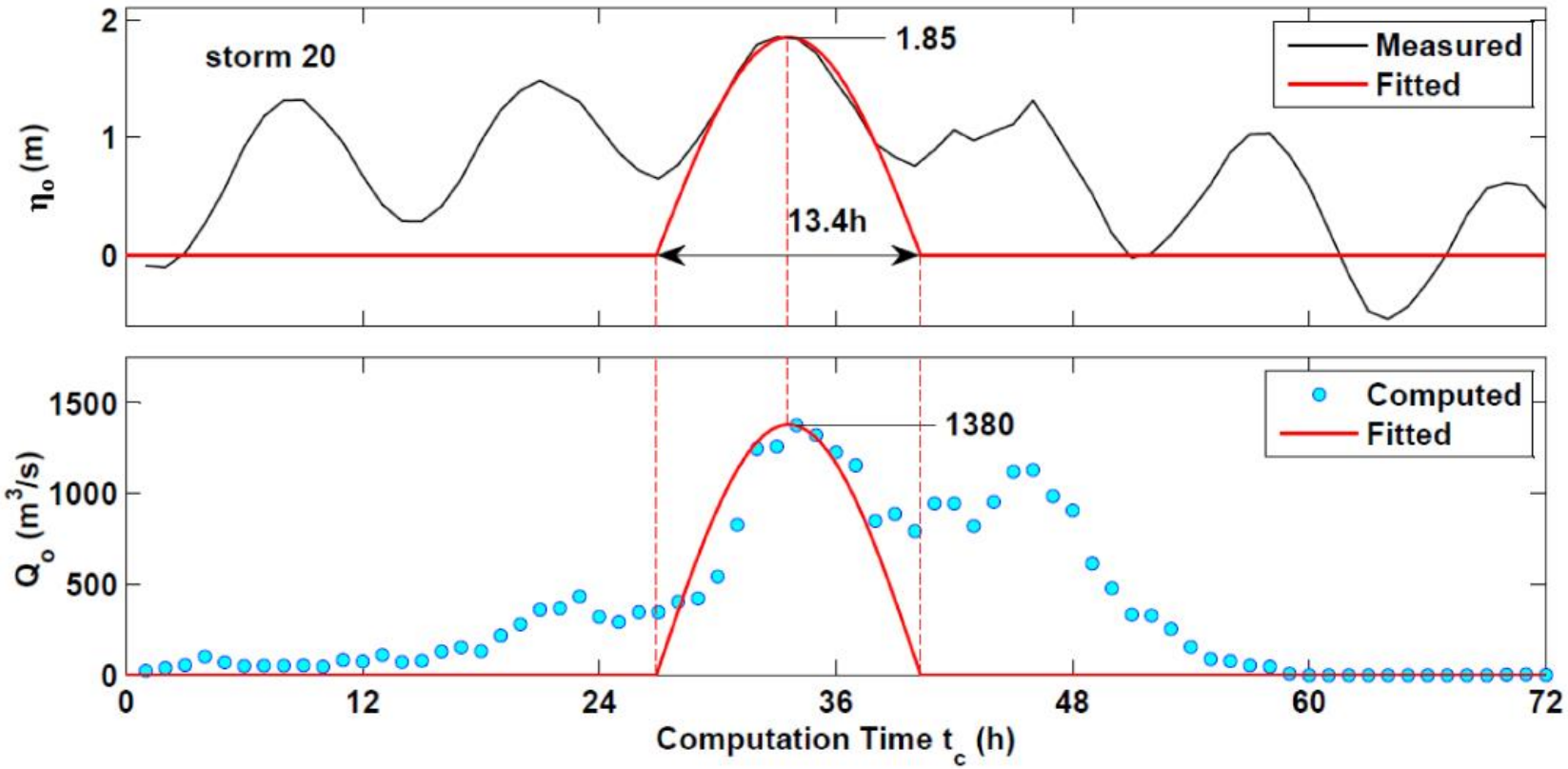
$$\eta_o(t) = \eta_m \sin\left(\frac{\pi t}{T_s}\right)$$

$$Q_w(t) = Q_m \sin\left(\frac{\pi t}{T_s}\right)$$

for $0 \le t \le T_s$

- Maximum wave overtopping rate Q_m = 1380 m^3/s

- Q_o = sum of ($q_o \times 515$ m) for 14 cross-shore lines



Measured and fitted ocean stillwater elevation η_o and computed and fitted wave overtopping rate Q_o over barrier beach of 7.2-km alongshore length

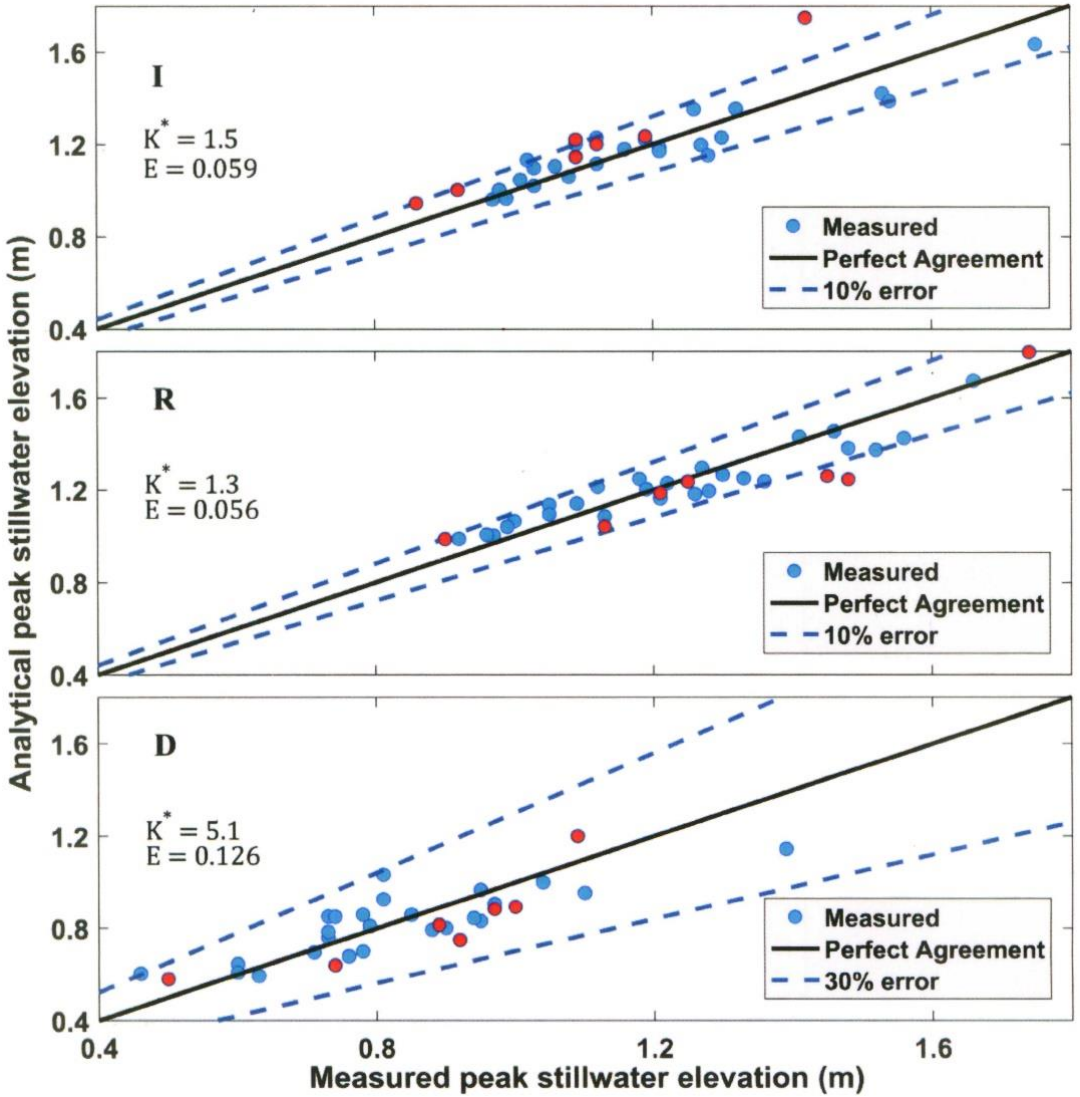
Analytical Model Including Wave Overtopping

Tide Gauge	K*	Peak Stillwater Elevation (m)		
		Measured η_p	Analytical η_p	
			no overtopping	with overtopping
L	-	1.85	1.85 (Input)	1.85 (Input)
I	1.5	1.75	1.63 (6.9%*)	1.76 (0.6%)
R	1.4	1.66	1.67 (0.6%)	1.79 (7.8%)
D	5.1	1.34	1.14 (14.9%)	1.36 (1.5%)

** Relative error between measured and analytical values*

- The total overtopping water volume is the order of 10^8 m^3, resulting in peak stillwater elevation increase of 0.1-0.2 m
- Increased η_B in the bay reduced water flux escape from the bay to the ocean through the tidal inlet

Verification of Calibrated Model



- 27 storms in 2005-2015
- 7 storms in 2016 and 2017

- Measured and analytical peak elevations η_p in bay at tide gauges I ($K^* = 1.5$), R ($K^* = 1.3$), and D ($K^* = 5.1$) with 10% or 30% error range and root-mean-square relative error E

Conclusions

- Simple analytical model for a small bay with a tidal inlet is developed to express bay peak stillwater elevation η_p as a function of ocean peak stillwater elevation η_m and storm surge duration T_s for given dimensionless inlet and bay parameter K^*
- Using the Calibrated K^* for each gauge, η_p is predicted within 10% errors in the Indian River Bay and within 30% errors in shallow Rehoboth Bay. The calibrated K^* was verified by additional 7 storms.
- Wave overtopping and overwash of barrier beach computed during Hurricane Sandy indicates total overtopping water volume of the order of 10^8 m^3, resulting in peak stillwater elevation increase of 0.1 – 0.2 m in bay
- The analytical model coupled with cross-shore CSHORE model was useful in evaluating bay flooding risk during extreme storms in an efficient manner
- The utility of the coupled approach will need to be demonstrated at other field sites with tide gauge data in the bay and ocean in the future work.