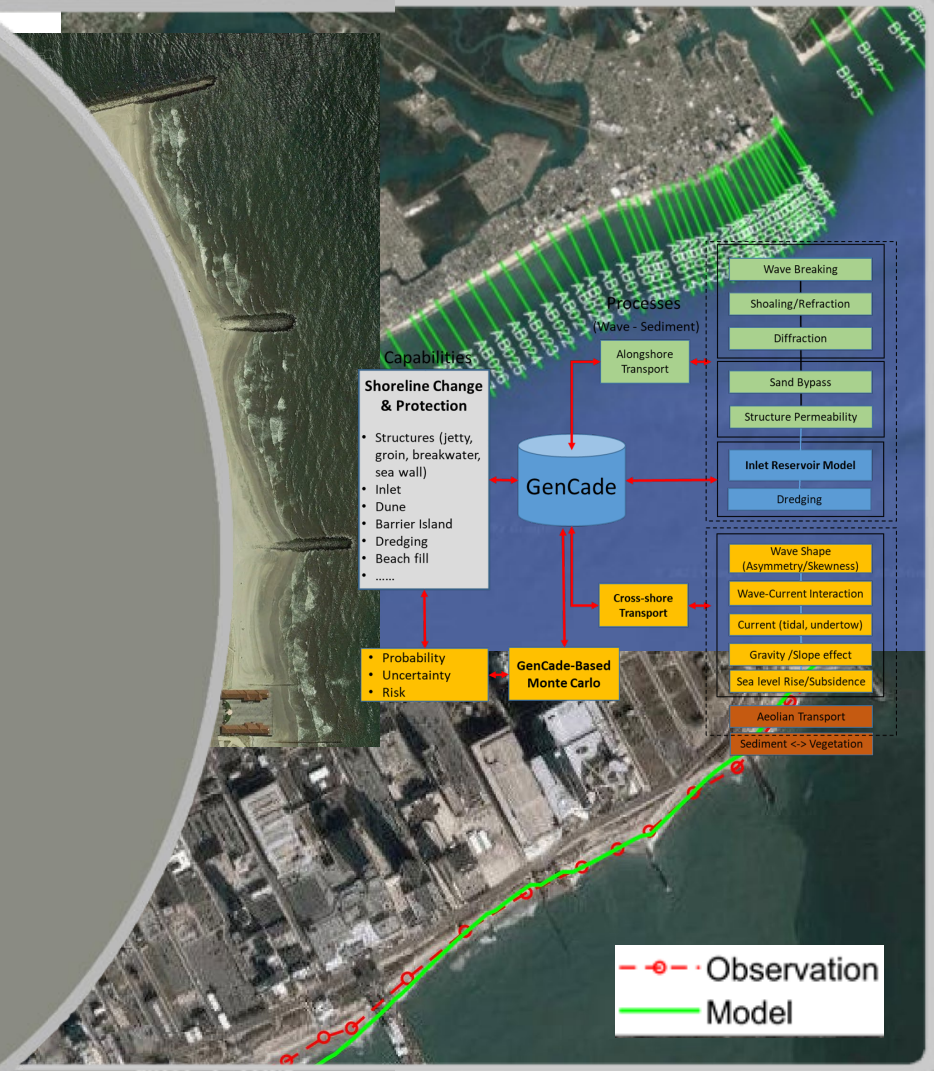
Modeling Long-term and Regional Shoreline Evolution around Coastal Inlet

Yan Ding, Ph.D.

Research Civil Engineer
U.S. Army Engineer Research and Development Center,
Coastal and Hydraulics Laboratory, Coastal Processes Branch,
Vicksburg, MS

CIRP-TD, Apr. 12, 2022



US Army Corps of Engineers®

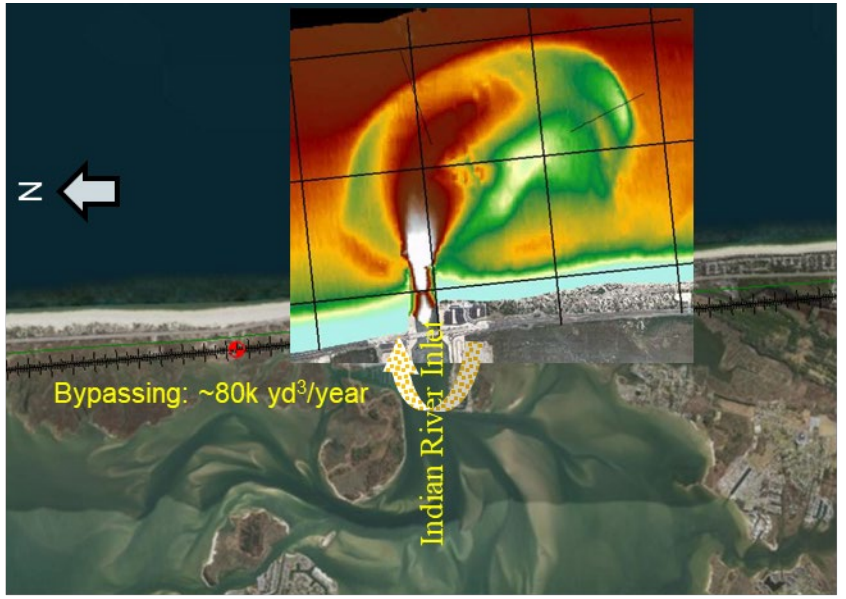
CIRP Mission Support Technology Transfer Research & Development

COASTAL AND HYDRAULICS LABORATORY

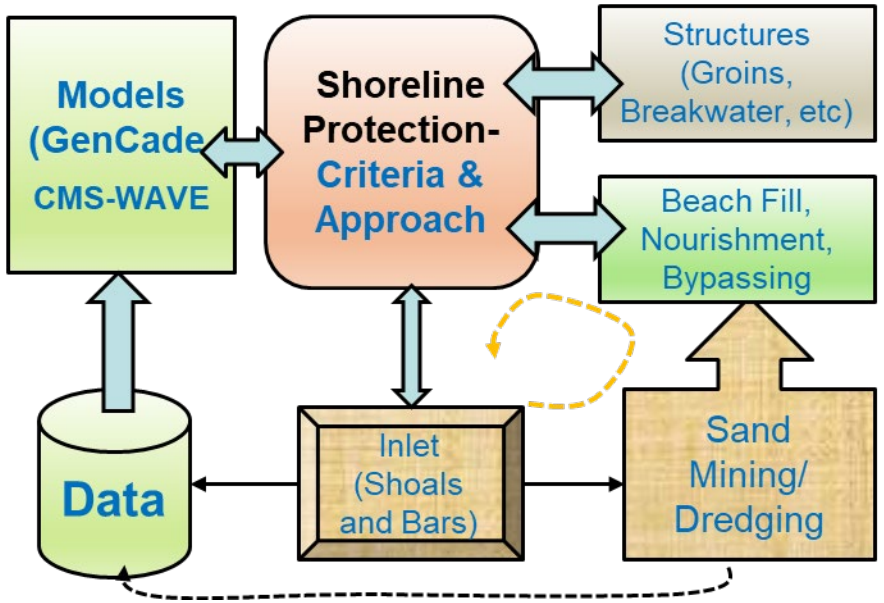
ERDC ENGINEER RESEARCH & DEVELOPMENT CENTER

Introduction

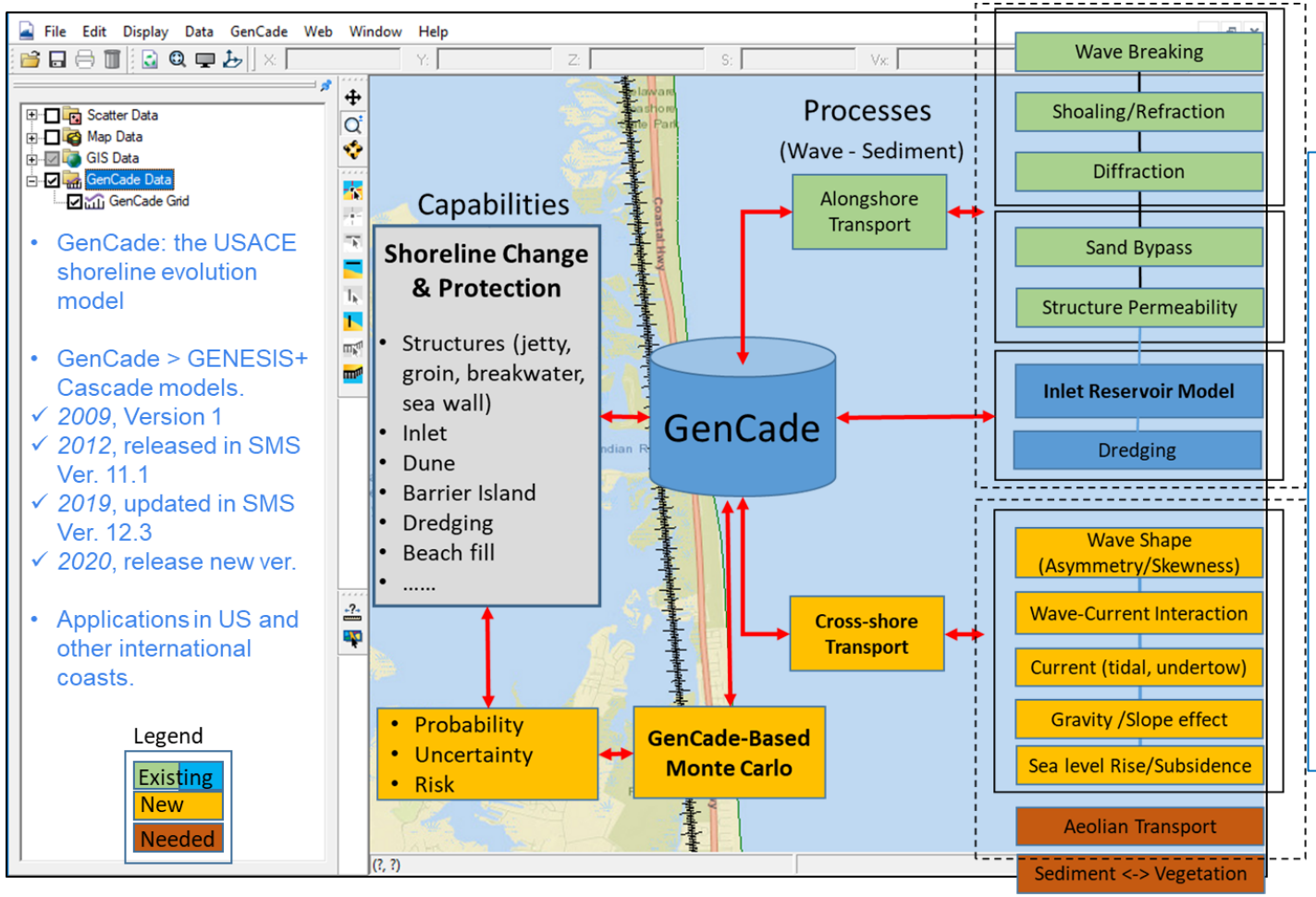
- Shoreline erosion protection requires quantitative information for long-term and regional shoreline evolution
  - Long-term: 1 ~ 10^2 years (≥ a life cycle)
  - Regional scale: 10~10^2 miles (~ a CSRM region)
- Importance and complexity of modeling long-term regional shoreline evolution in barrier islands
  - Modeling capabilities for long-term shoreline evolution, engineering protection measures (structures, beach fills)
  - Sediment exchanges between inlet morphology elements and adjacent shorelines, and induced by inlet shoal/bar dredging/mining
- Application examples of modeling shoreline evolution and inlet morphology: (1) Indian River Inlet, DE, and (2) Absecon Inlet, NJ
- Remarks



GenCade x-axis



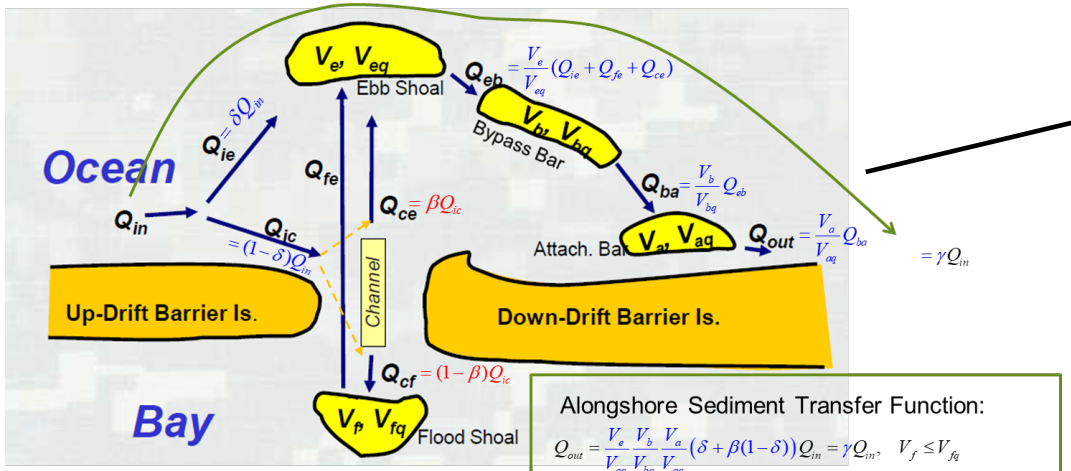
Model Capabilities: GenCade - USACE Shoreline Evolution Simulation Model



Principal Features of GenCade

- For modeling long-term and regional shoreline evolution driven by long- & cross-shore transport
- Simulation of hard structure effects on shoreline changes → groins, breakwaters, jetties, seawall
- Simulation of soft structure effects → beachfills, nourishment, sediment bypassing
- Simulation of inlet morphology element evolution, including dredging/mining in shoals and bars.
- SMS supports development of GenCade model, GenCade Version 1r8 in SMS Ver. 13.1
- User manual, technical transfer, customer service

Inlet Reservoir Model and Inlet Morphologic Features



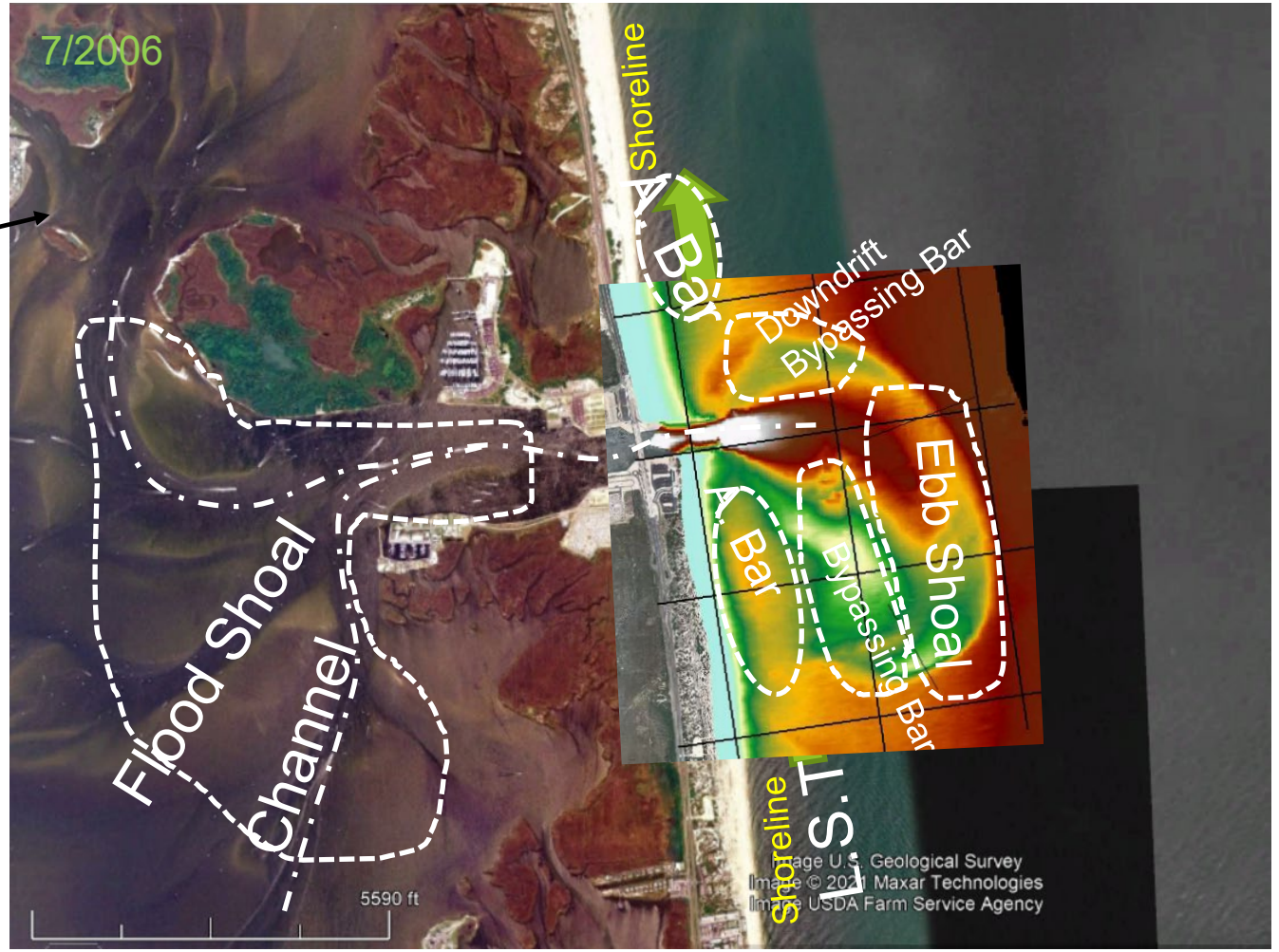
$$Q_{fe} = \begin{cases} (V_f - V_{fq})/dt & V_f > V_{fq} \\ 0 & V_f \le V_{fq} \end{cases}$$

Alongshore Sediment Transfer Function:

$$Q_{out} = \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} (\delta + \beta(1-\delta)) Q_{in} = \gamma Q_{in}, \quad V_f \le V_{fq}$$

$$Q_{out} = \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} \left[(\delta + \beta(1-\delta)) + \frac{V_f - V_{fq}}{Q_{in} dt} \right] Q_{in} = \gamma' Q_{in}, \quad V_f > V_{fq}$$

- Two Transfer Factors exist: γ_{left}, and γ_{right}.



Indian River Inlet, DE

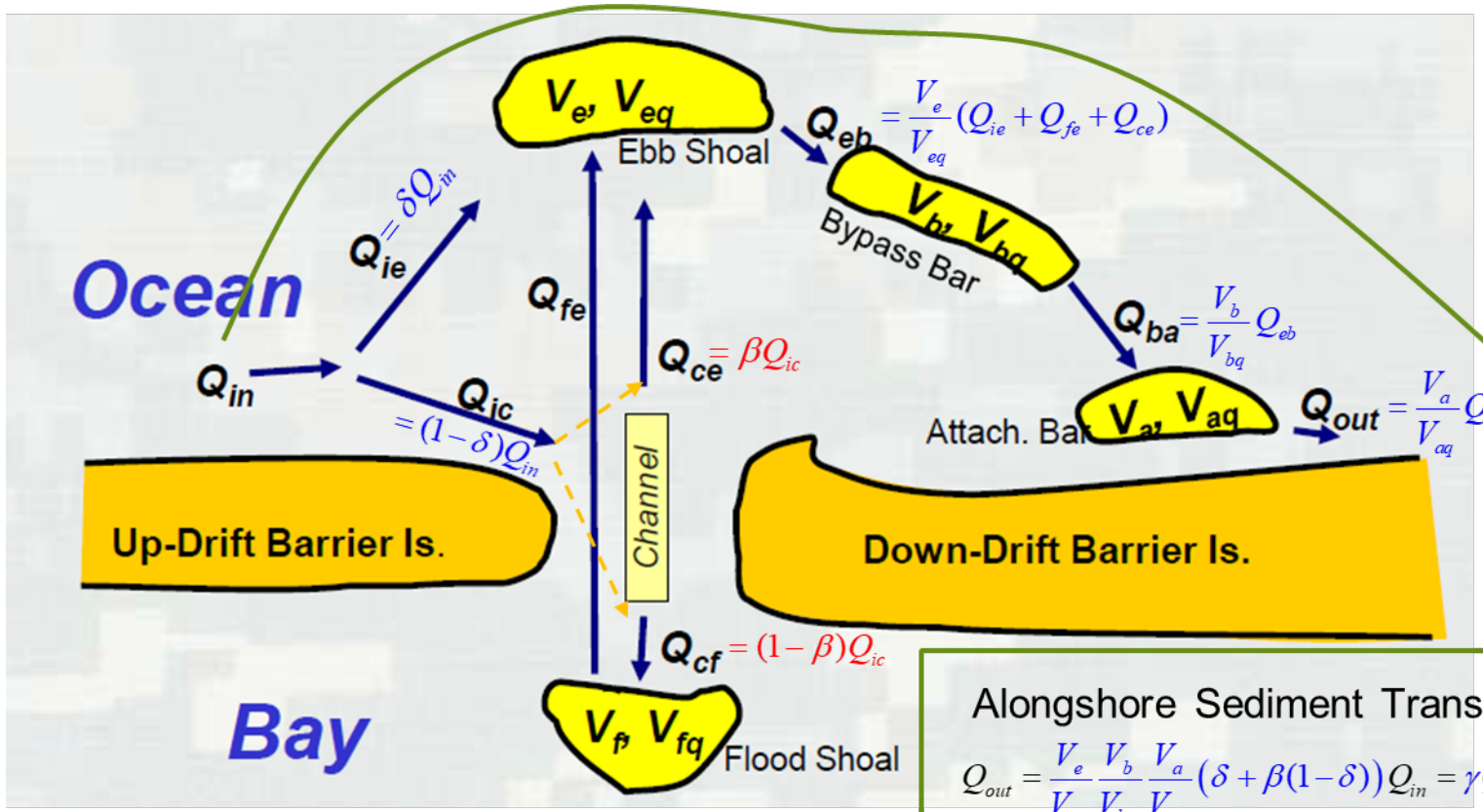
Inlet Reservoir Model (IRM)
for Simulation of Inlet Morphology Evolution

Parameters required: V_{x0} =initial volumes

V_{xq} =equilibrium volumes

Q_{in} =Long-shore Sediment Transport (LST)

Inlet Reservoir Model Inlet
Evolution of Shoals and Bars, Bypassing, and Sediment Pathways



$$Q_{fe} = \begin{cases} (V_f - V_{fq})/dt & V_f > V_{fq} \\ 0 & V_f \le V_{fq} \end{cases}$$

Alongshore Sediment Transfer Function:

$$Q_{out} = \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} (\delta + \beta(1-\delta)) Q_{in} = \gamma Q_{in}, \quad V_f \le V_{fq}$$

$$Q_{out} = \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} \left[(\delta + \beta(1-\delta)) + \frac{V_f - V_{fq}}{Q_{in} dt} \right] Q_{in} = \gamma' Q_{in}, \quad V_f > V_{fq}$$

- Two Transfer Factors exist: γ_{left}, and γ_{right}.

Application Examples

Case 1: Simulation of Shoreline Changes around Indian River Inlet (IRI), DE

Features: Sand bypass operation, post-storm nourishment

Case 2: Simulation of Shoreline Changes around Absecon Inlet, NJ

Features: Beachfills, structures (groins, breakwater, outfalls, jetties), ebb shoal dredging

(1) Indian River Inlet and Sand bypass, DE

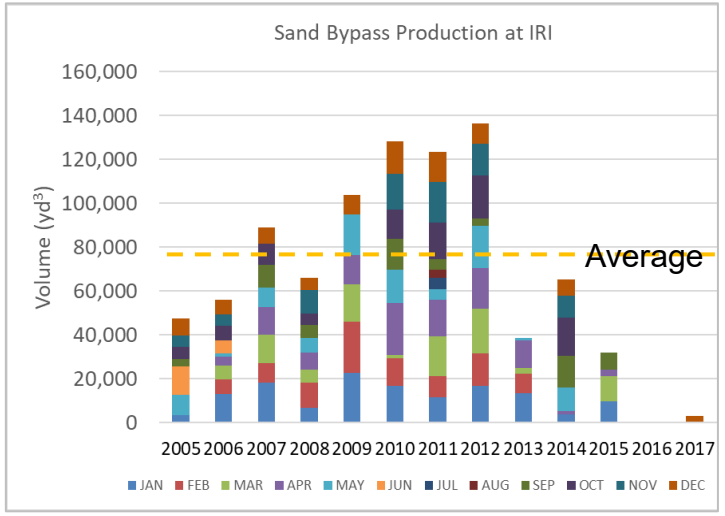
(2) Absecon Inlet, NJ

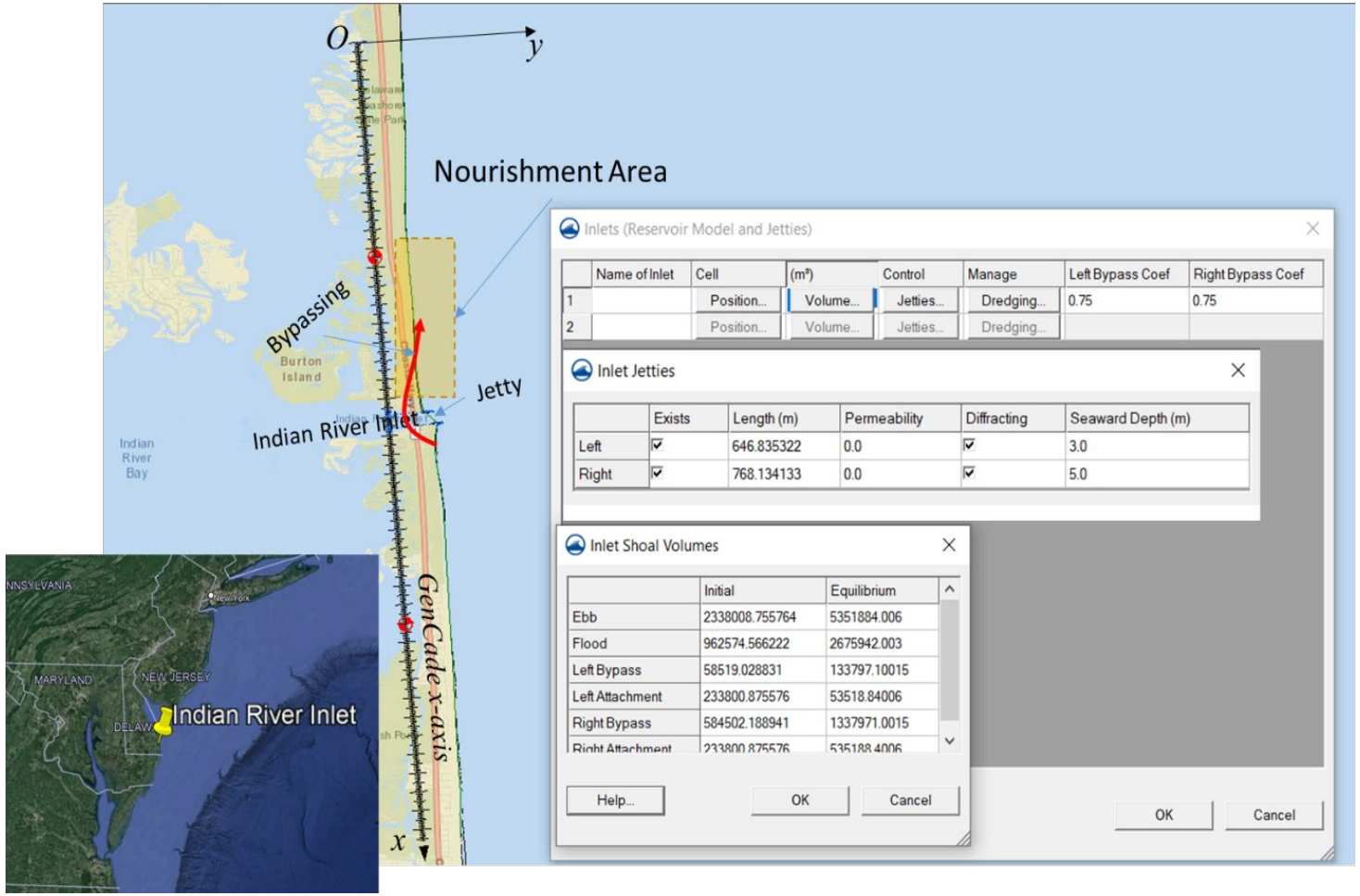
Case 1: Shoreline Evolution around IRI: A GenCade Model for Indian River Inlet

Objectives:

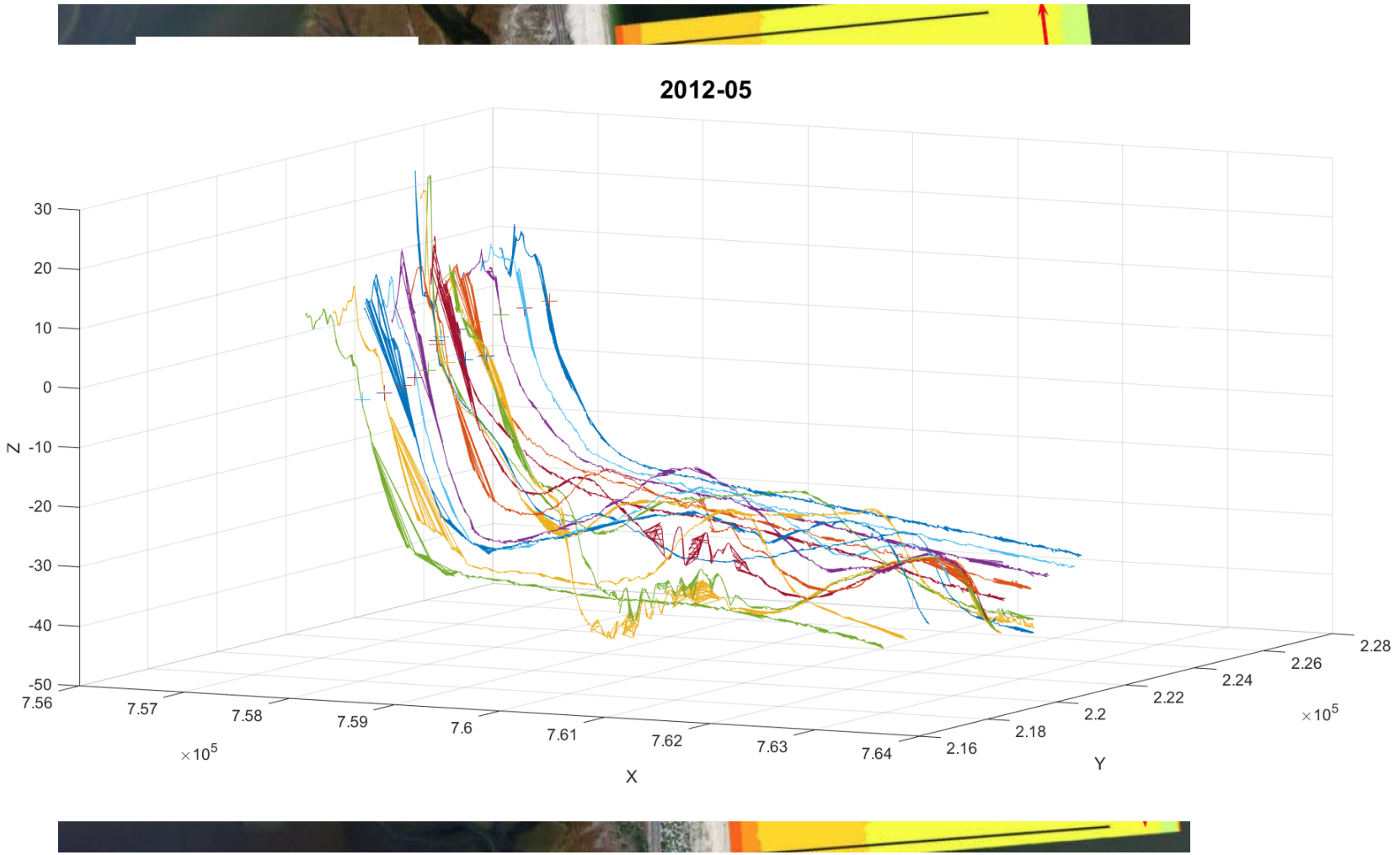
(1) To validate the GenCade model by using shoreline survey data provided by NAP and DNREC, and

(2) To evaluate sand bypass operation.





Transect Survey Data in Coasts near Indian River Inlet (2005-2017)



Gebert (2006), presentation in ASBPA 2006

Sediment Bypassing Operation and Nourishment

Model Parameters:

Computational Period: 12 years
2005/03/12 0:00 - 2016/12/31 0:00
Including beach construction projects:
Sand Bypassing: ~80,000 yd^3 / year
Beach nourishment: 527,850 yd^3, May-Nov 2013
Wave Conditions: WIS #63158 (depth=18m)

Time step = 3 minutes
Grain size = 0.30 mm
Berm Height = 2.0 m
Closure depth = 10.0m
Smooth parameter = 5
No regional contour
Boundary Conditions: no moving b.c.s.
Grid Size = 25 m

Calibrated Model Parameters:
K1 = 0.17 at the north of inlet, 0.35 at south
K2 = 0.085 at the north, 0.175 at the south

Inlet Reservoir Model: 12 parameters

No cross-shore transport included

Evolution of Inlet Morphology Elements (Shoals and Bars)

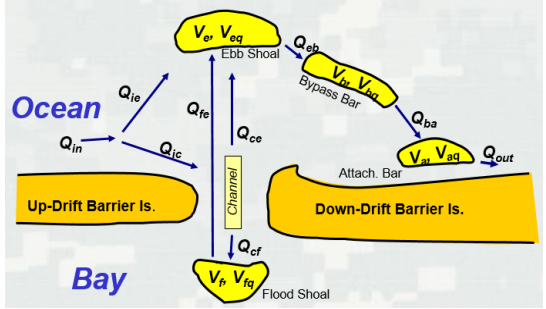
Estimated IRM parameters for IRI

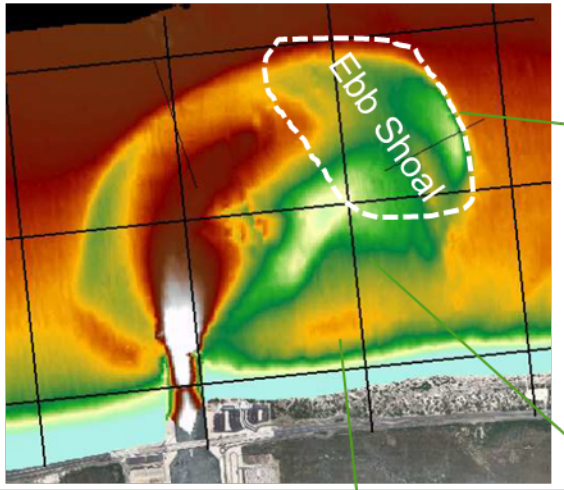
	Initial (Cyd)	Equilibrium (Cyd)
ebb	4,900,000	7,000,000
flood	2,800,000	3,500,000
left bypass	76,540	175,000
left attachment	56,000	70,000
right bypass	764,500	1,750,000
right attachment	305,800	700,000

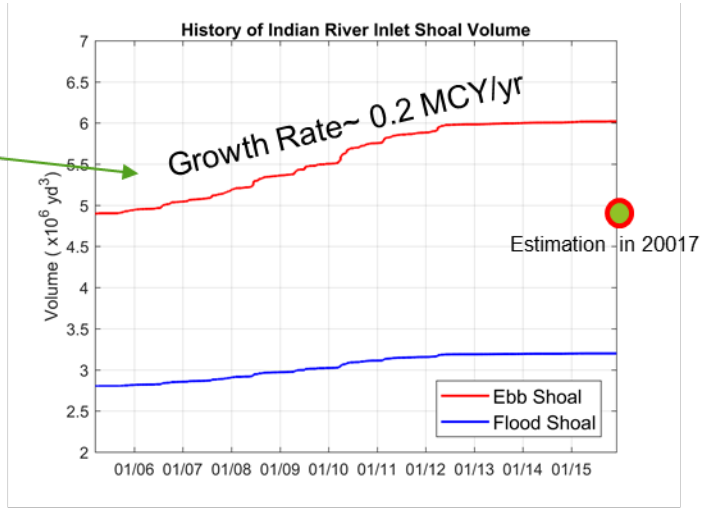
From hydro survey:

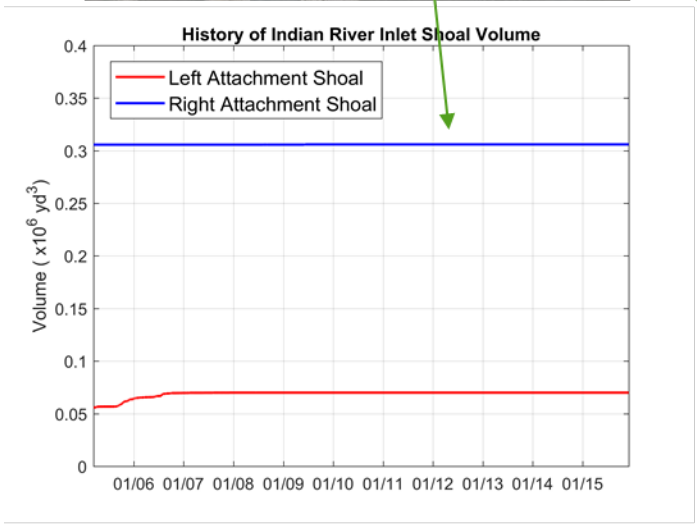
- Ebb Shoal Volume (V_e): ~4.7 MCY in 2017 (Mann et al. 2017, CB&I).
  Equilibrium (V_{eq}): ~7.0 Mcy (Larson et al. 2006)
- Flood Shoal Volume ?

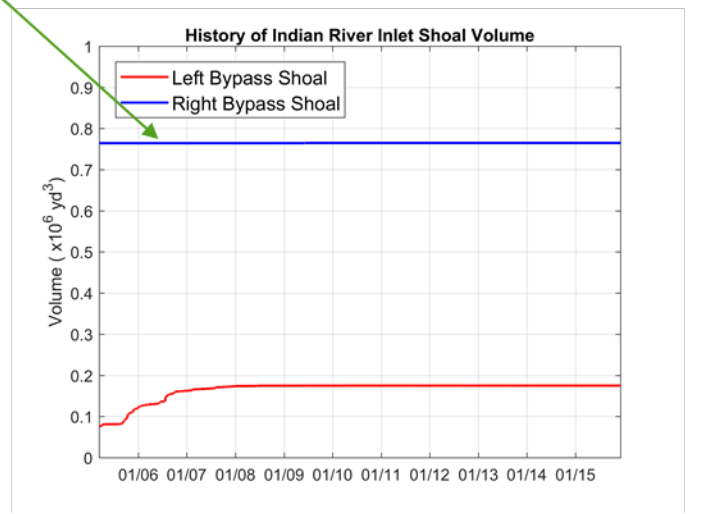
Inlet Reservoir Model



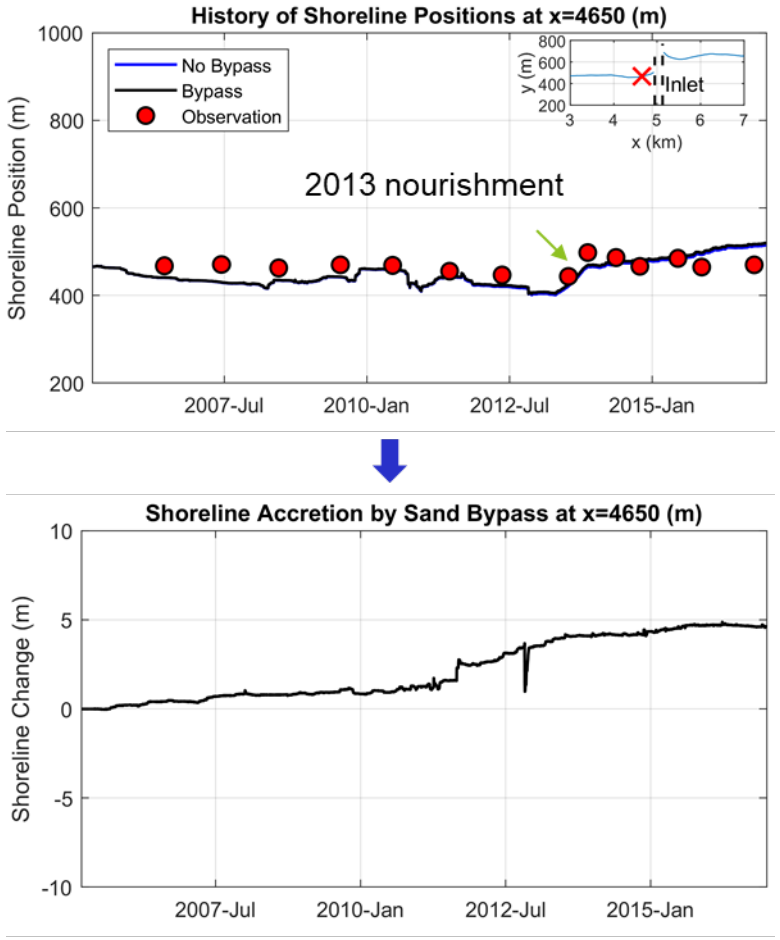




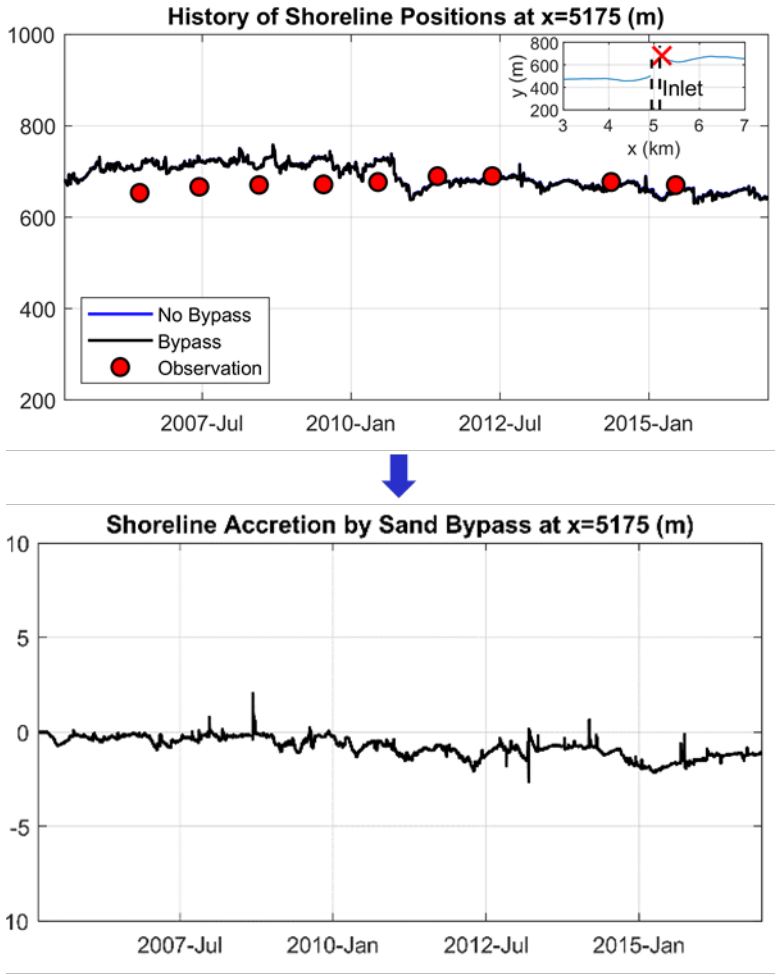




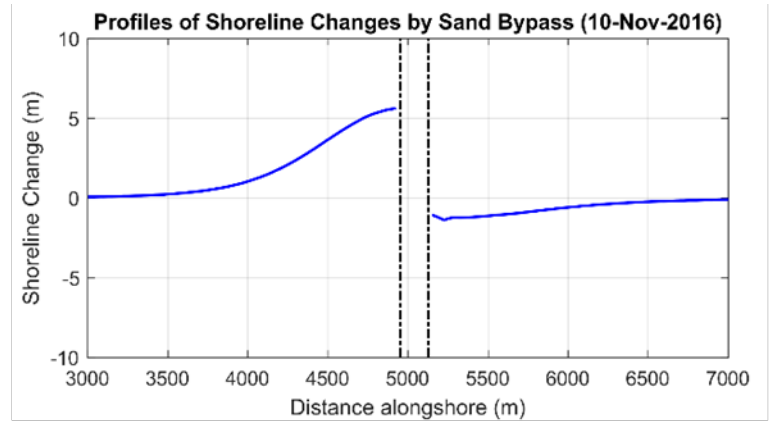
Effect of Sand Bypassing Operation

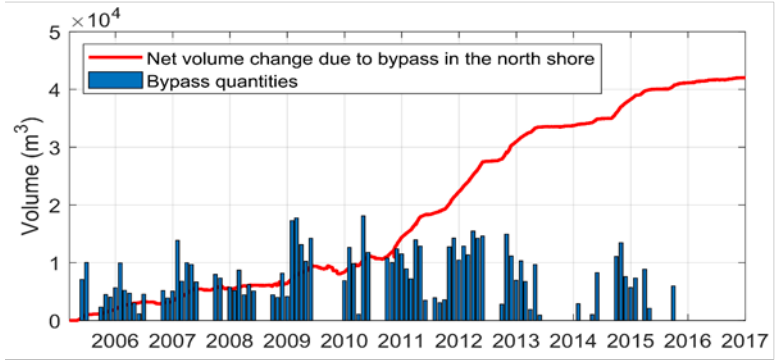


(a) North Shore



(b) South Shore



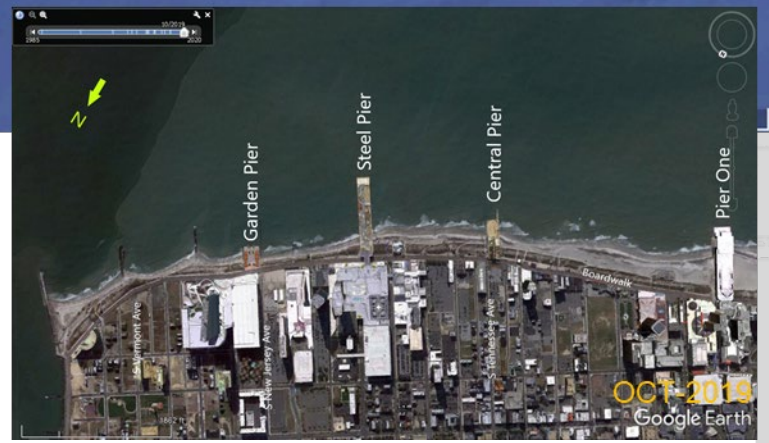


(c) Net volume of bypass sand in north shore. The bars show the monthly bypass Rate.

Case 2: Simulation of Shoreline Evolution around Absecon Inlet, NJ

Problems

- Persistent shoreline erosion occurs at the northeast end of Atlantic City, often called the erosion hot spot (EHS).
- For erosion protection, hard structures (groins, breakwater, jetties) have been constructed, periodical beach fills and post-storm nourishment have been performed along Absecon Island, focused on the EHS.
- Persistent erosion of dune, berm, and beach sands has significantly reduced storm damage reduction capabilities that the project should provide and has significantly impacted public access.



Project Objectives

1. To identify principal factors that contribute to the EHS by learning from survey data and developing a shoreline evolution (GenCade) model;
2. By using the validated shoreline model to study feasibility of the design alternatives that can reduce and eliminate the EHS and maintain the authorized CSRM beach fill template between nourishment cycles.

Construct Historical Shoreline Positions at MHW on NAP Monitoring Lines

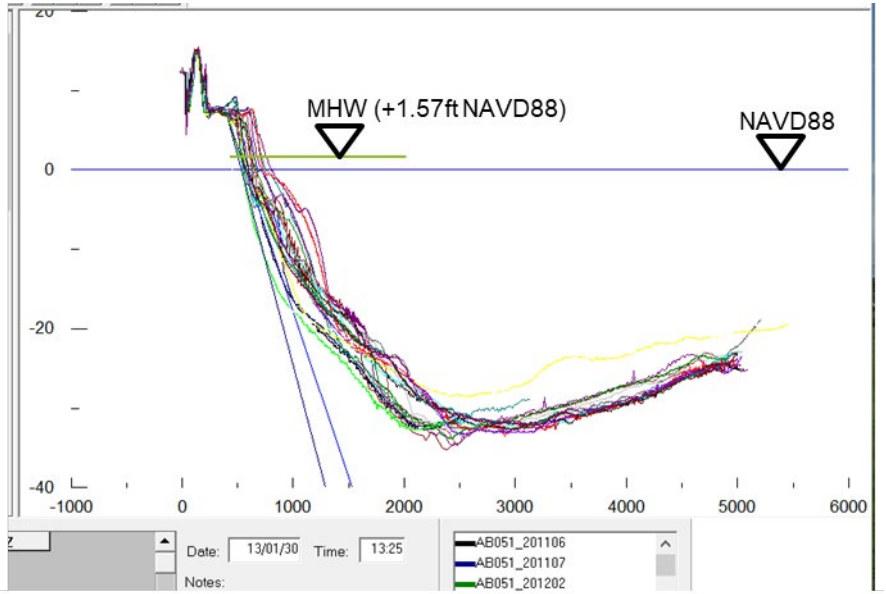
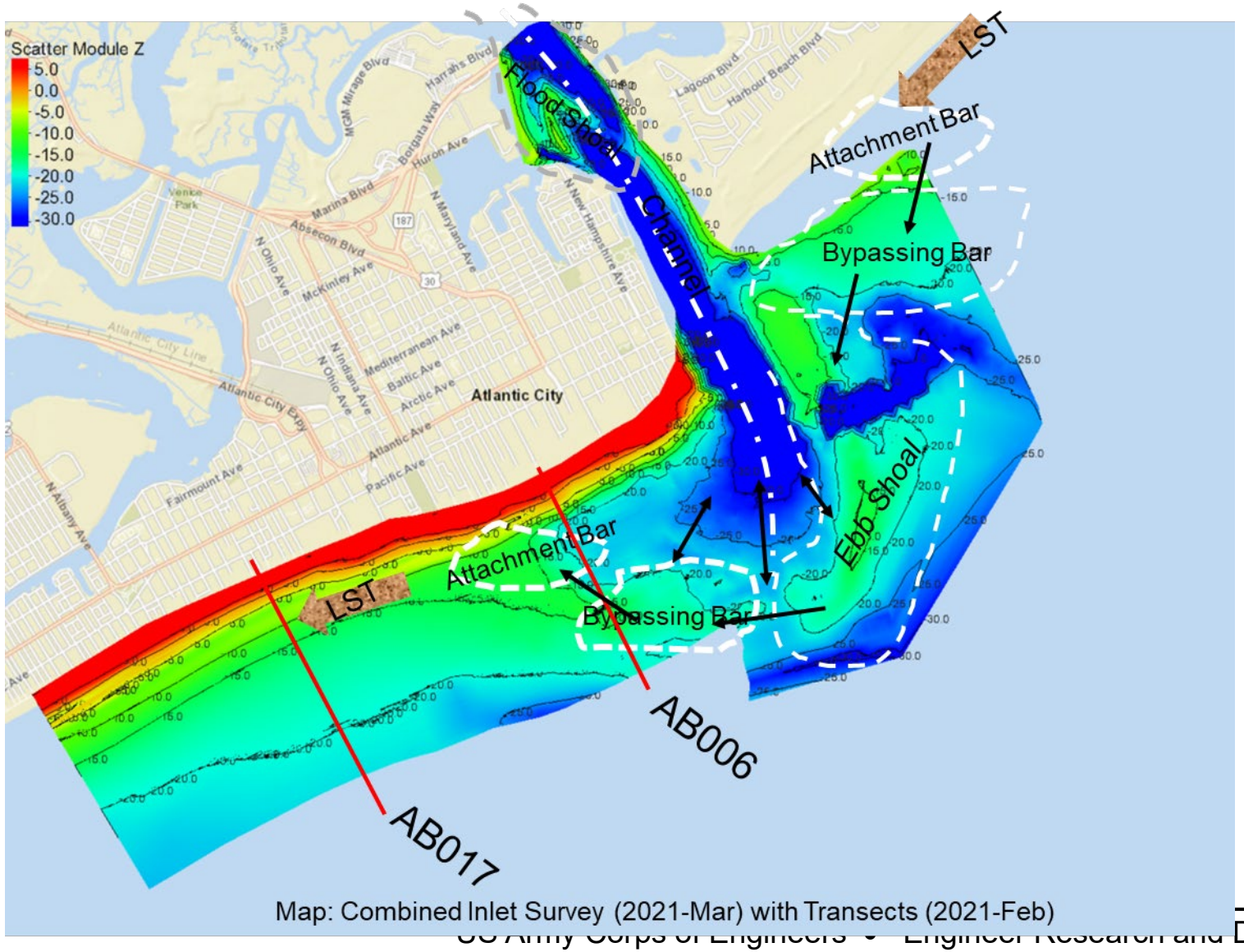


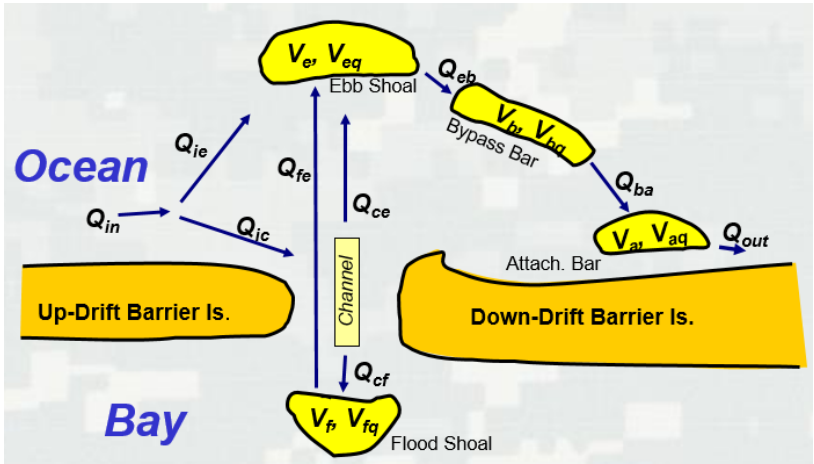
Table. Transect surveys (2003-2021)

Season	Absecon	Brigantine
Spring	1	1
Summer	6	2
Autumn	10	14
Winter	4	2
Total	21	19

Identify Absecon Inlet Morphologic Features for Developing Absecon IRM



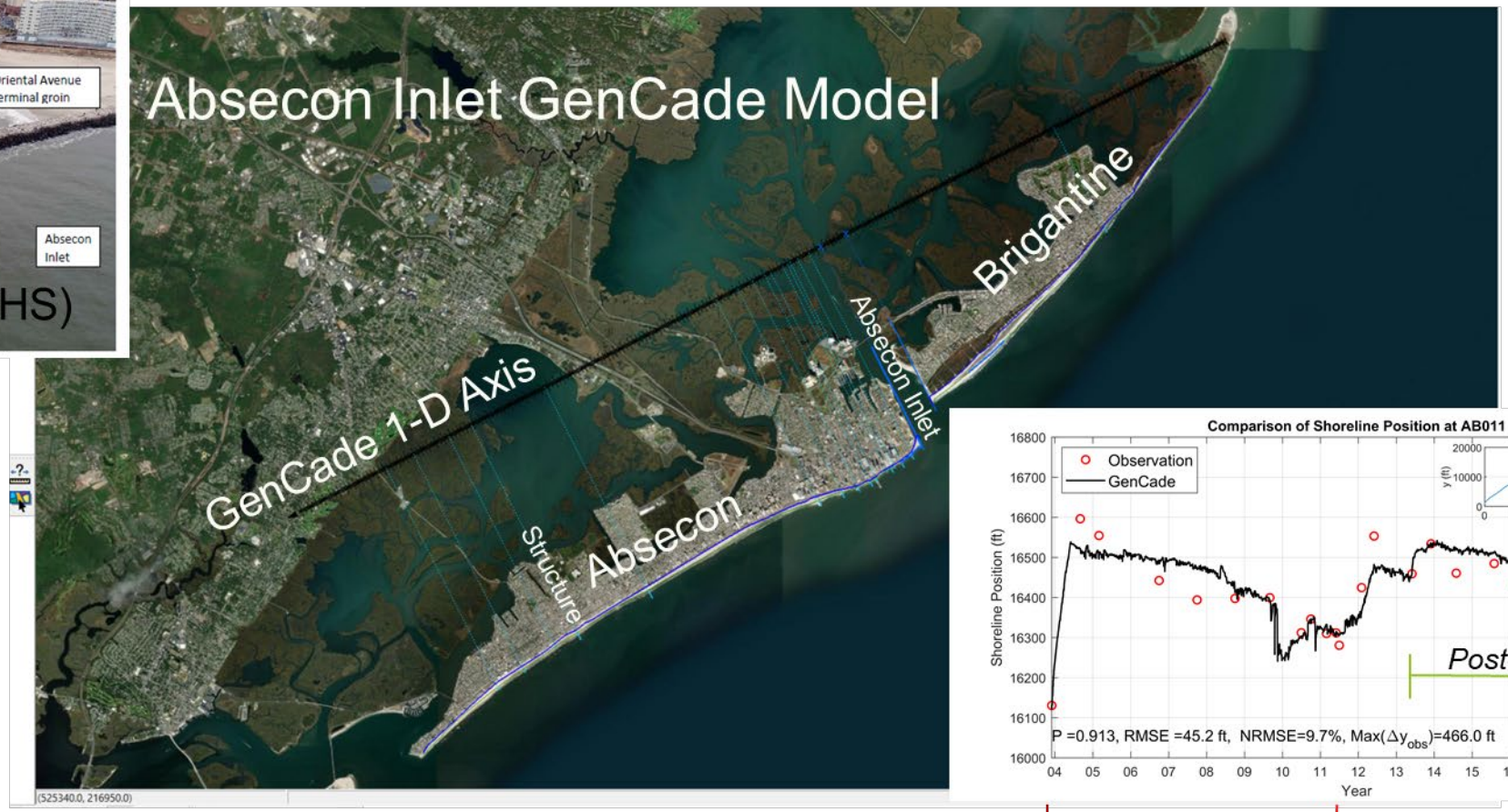
Map: Combined Inlet Survey (2021-Mar) with Transects (2021-Feb)



Inlet Reservoir Model (IRM)
for Simulation of Inlet Morphology Evolution

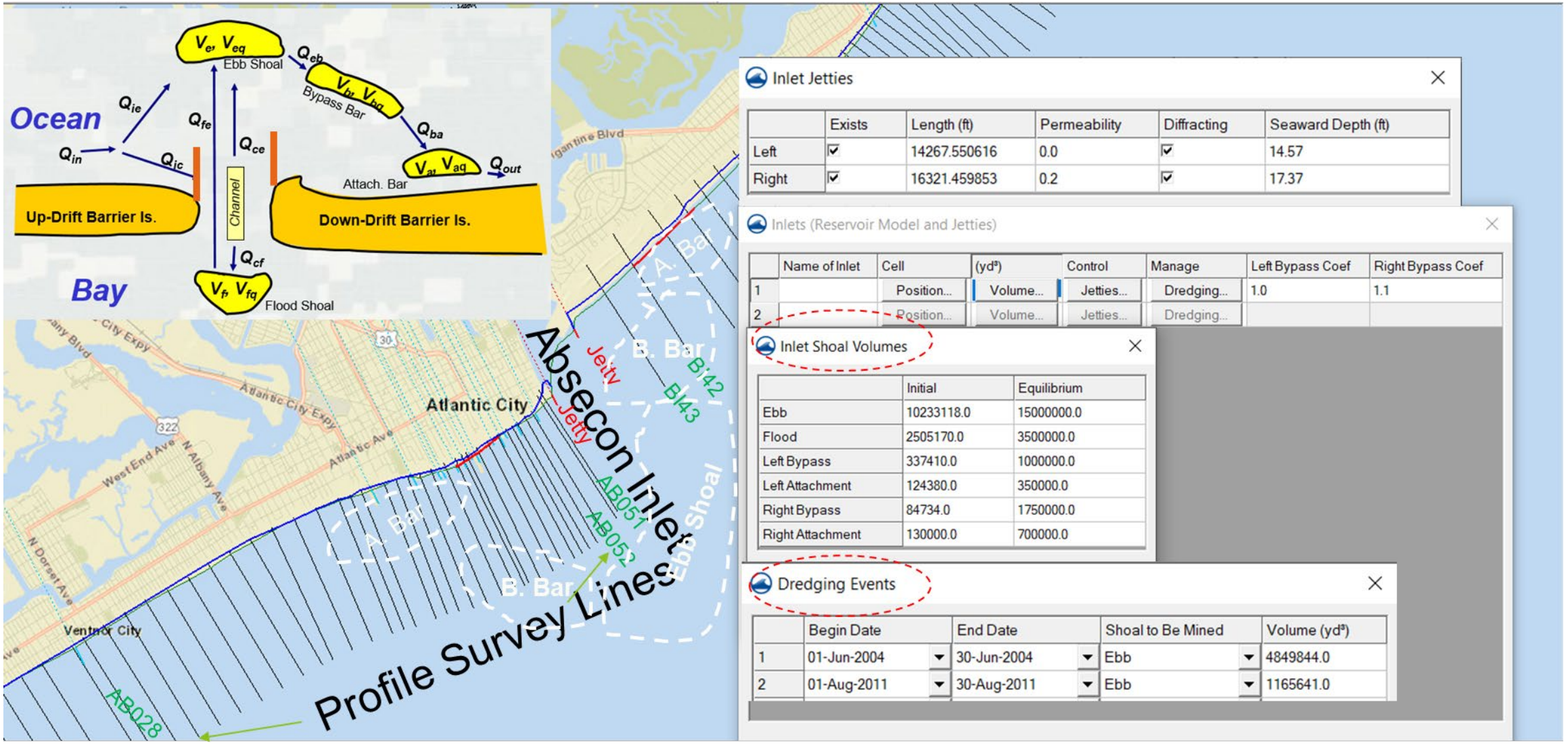
GenCade Model Development

Calibration: 2003-2011
Validation: 2011-2019



Length (L)=14.1 miles
Grid space (Δx)=60 ft
Grid size (N) = 1243 transects

Inlet Reservoir Model (IRM) and Dredging



	Exists	Length (ft)	Permeability	Diffracting	Seaward Depth (ft)
Left	☑	14267.550616	0.0	☑	14.57
Right	☑	16321.459853	0.2	☑	17.37

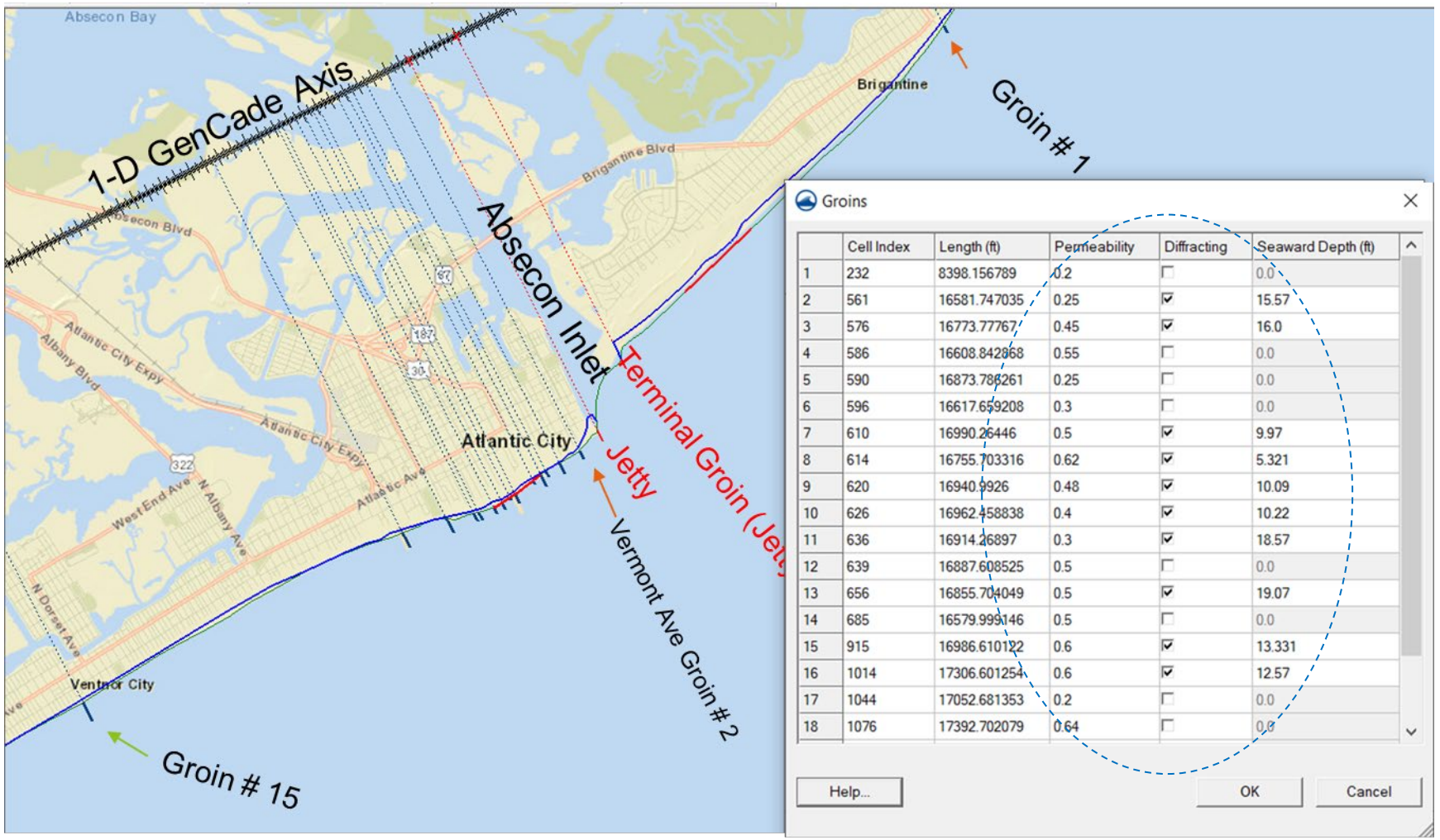
	Name of Inlet	Cell	(yd³)	Control	Manage	Left Bypass Coef	Right Bypass Coef
1		Position...	Volume...	Jetties...	Dredging...	1.0	1.1
2		Position...	Volume...	Jetties...	Dredging...		

	Initial	Equilibrium
Ebb	10233118.0	15000000.0
Flood	2505170.0	3500000.0
Left Bypass	337410.0	1000000.0
Left Attachment	124380.0	350000.0
Right Bypass	84734.0	1750000.0
Right Attachment	130000.0	700000.0

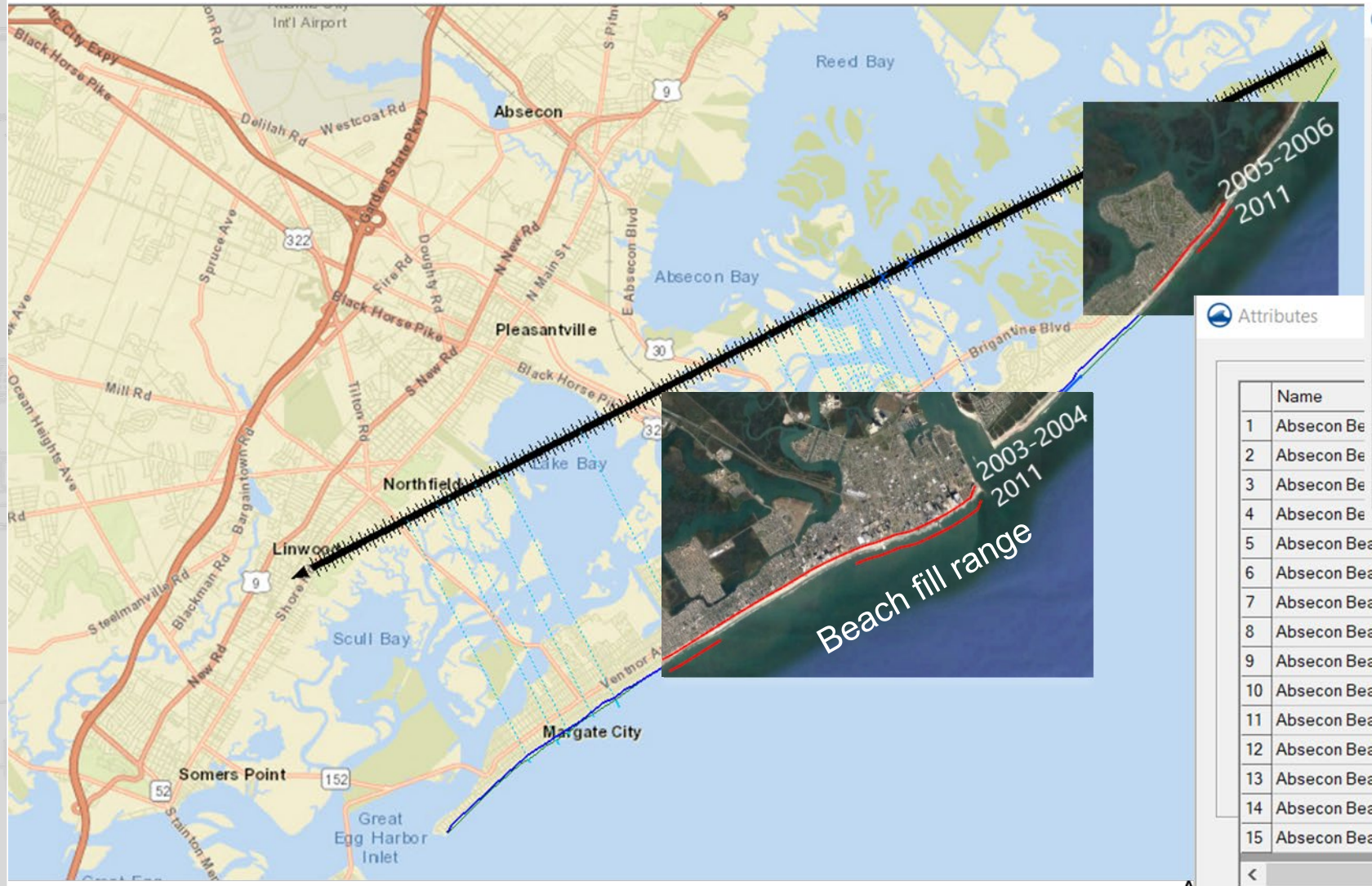
	Begin Date	End Date	Shoal to Be Mined	Volume (yd³)
1	01-Jun-2004	30-Jun-2004	Ebb	4849844.0
2	01-Aug-2011	30-Aug-2011	Ebb	1165641.0

Calibrated Parameters for Estimating Structure's effect on LST

- **Diffracting Structures**: Groins, Piers
- Non-Diffracting Structures: Short groins, outfalls
- **Seaward depth** at the tip of groin is given from transect profile near the structure
- **Length:** the distance from the seaward tip to the GenCade 1-D Axis.
- **Permeability** (sand transmission capability through the structure): **calibrated**



Beach Fills in Calibration Period (2003-2011)



Beach Fill

	Begin Date	End Date	Start Cell	End Cell	Added Berm Width (ft)
1	01-Nov-2005	01-Sep-2006	146	161	96.58
2	01-Nov-2005	01-Sep-2006	161	176	140.49
3	01-Oct-2011	01-Jan-2012	161	176	55.05
4	01-Dec-2017	01-Apr-2018	161	176	317.94
5	01-Nov-2012	01-Jun-2013	161	176	172.88
6	01-Nov-2005	01-Sep-2006	176	183	171.52
7	01-Oct-2011	01-Jan-2012	176	183	39.63
8	01-Nov-2012	01-Jun-2013	176	183	378.76
9	01-Dec-2017	01-Apr-2018	176	183	479.81
10	01-Nov-2005	01-Sep-2006	183	191	177.92
11	01-Dec-2017	01-Apr-2018	183	191	360.48
12	01-Oct-2011	01-Jan-2012	183	191	50.47
13	01-Nov-2012	01-Jun-2013	183	191	439.11
14	01-Nov-2005	01-Sep-2006	191	198	179.97
15	01-Nov-2012	01-Jun-2013	191	198	408.78
16	01-Dec-2017	01-Apr-2018	191	198	279.78
17	01-Oct-2011	01-Jan-2012	191	198	73.93
18	01-Nov-2005	01-Sep-2006	198	206	163.32

Attributes

	Name					
1	Absecon Be					
2	Absecon Be					
3	Absecon Be					
4	Absecon Be					
5	Absecon Beach Fill Range	Feb-2012	Jun-2012	110.869133	AB025	AB033
6	Absecon Beach Fill Range	Jun-2013	Dec-2013	101.829072	AB051	AB012
7	Absecon Beach Fill Range	Jun-2013	Dec-2013	65.419285	AB014	AB033
8	Absecon Beach Fill Range	Apr-2017	Sep-2017	89.402910	AB051	AB024
9	Absecon Beach Fill Range	May-2017	Sep-2017	49.782800	AB025	AB032
10	Absecon Beach Fill Range	Jun-2017	Jan-2018	174.625111	AB033	AB041
11	Absecon Beach Fill Range	Oct-2017	May-2018	158.458487	AB042	AB049
12	Absecon Beach Fill Range	Sep-2020	Jan-2021	174.537400	AB029	AB032
13	Absecon Beach Fill Range	Sep-2020	Dec-2020	81.448550	AB033	AB034
14	Absecon Beach Fill Range	Nov-2020	Dec-2020	41.856267	AB047	AB049
15	Absecon Beach Fill Range	Nov-2020	Feb-2021	228.729285	AB051	AB014

- Added berm width was estimated from the measured shoreline changes

Model Calibration (2003-2011)

Objectives:

(1) to calibrate the empirical parameters:
- two longshore sediment transport rate (CERC formula) parameters (K_1 and K_2),
- permeability parameters of structures,

(2) to determine diffracting feature of each structure,

(3) to find a longer time step to optimize simulation efficiency, and

(4) to verify the IRM model parameters (volumes of shoals & bars)

Table 1. Absecon Island Beachfill Placement since Initial Construction in 2003 (NAP Report)

Beachfill Dates	Atlantic City	Ventnor	Margate	Longport	Total	Notes
Dec 2003-June 2004	3,600,000	1,260,000	0	0	4,860,000	
Mar-July 2011	1,003,000	0	0	0	1,003,000	Vermont to North Carolina Aves. in AC
Feb-Jun 2012	955,000	375,000	0	0	1,330,000	
Jun to Dec 2013	791,000	530,000	0	0	1,321,000	
May-Aug 2017	1,249,000	353,000	1,000,000	867,000	3,469,000	
Dec 2020 - Feb 2021	1,296,000	550,000	85,000	141,000	2,072,000	
Dec 2003 - Feb 2021	8,894,000	3,068,000	1,085,000	1,008,000	14,055,000	

Table 2. Brigantine Island Beachfill Placement since Initial Construction in 2006 (NAP Report)

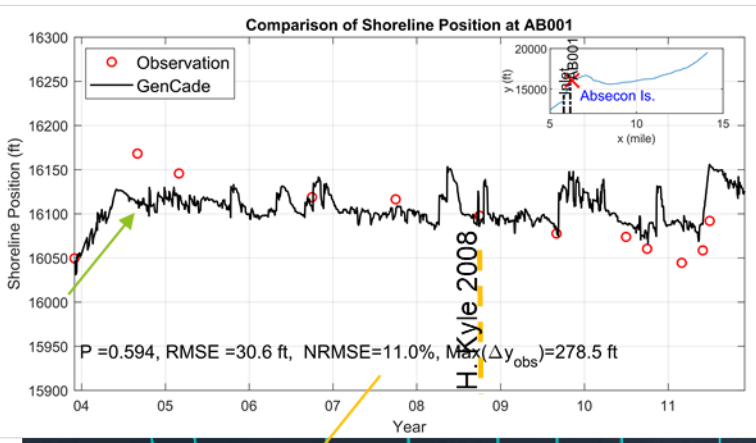
Construction	Date Completed	Pay Quantity, cy
Initial (including 1st periodic renourishment)	Feb 2006	671,000
FCCE emergency rehab	Dec 2011	94,000
2nd periodic renourishment	Dec 2012	500,000
FCCE restoration ("repair/restore" project Hurricane Sandy)	Jul 2013	427,000
3rd periodic renourishment and FCCE restoration	Apr 2018	755,000

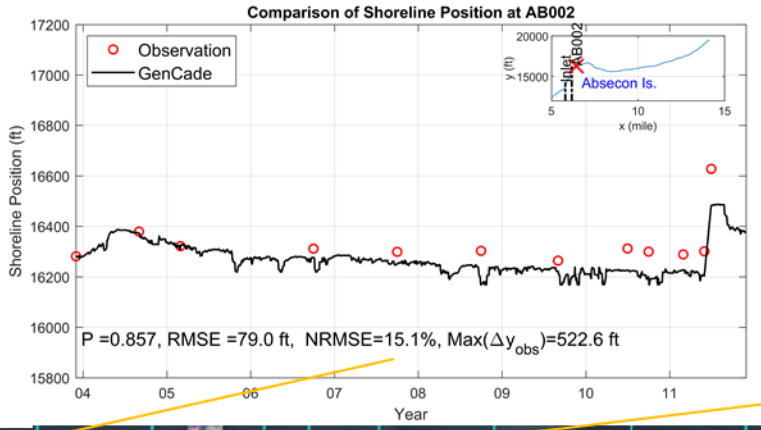
Conditions and Values:

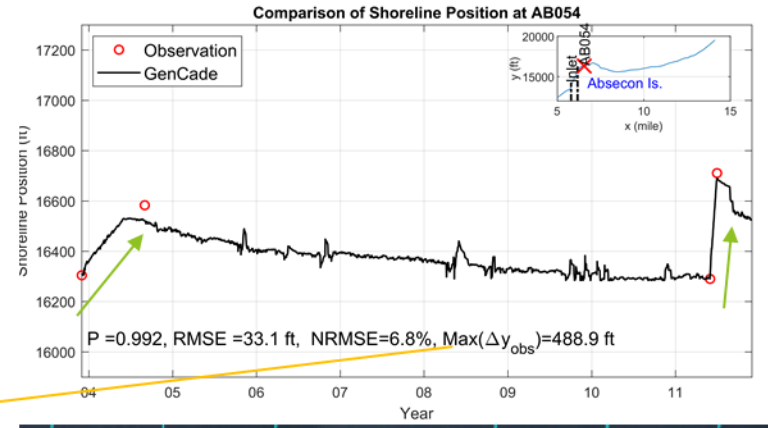
Computational Period: 8 years
2003/12/01 0:00 - 2011/12/01 0:00
Including beach construction projects (2003-2011):
Absecon: Initial Construction (Dec 2003-June 2004), Mar - July 2011
Brigantine: Initial construction (Nov. 2005 ~Feb 2006), Oct. 2011~Dec. 2011)
- GenCade requires added berm width as input parameter for each beach fill construction. The actual berm width extensions were determined by survey data at NAP monitoring lines. The berm width increases at those model transects between two lines were linearly interpolated from the survey data at two lines.

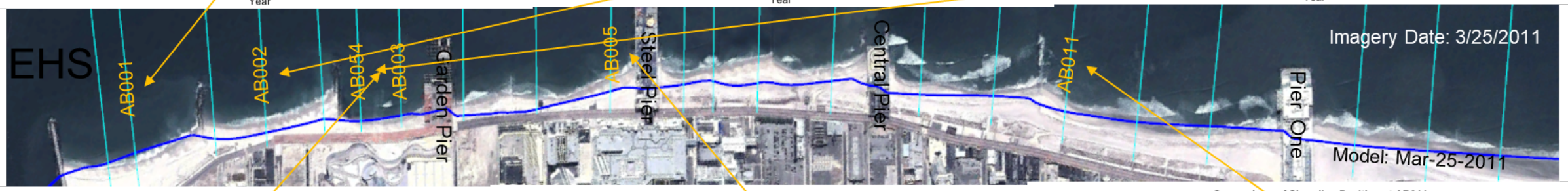
Offshore Waves: WIS 62141 (BI07-AB017) WIS 63142 (AB018-049)
Time step (Δt) = 90 seconds
Grid Size (Δx) = 60 ft
Grain size (d_{50}) = 0.25 mm
Berm Height (D_b) = 5.68 ft (above MHW, or 7.25 ft + NAVD88)
(*Based on beachfill template)
Closure depth (D_c) = 20.1 ft on Brigantine, 26.51 ft on Absecon
(*based on estimates by (Brutsche et al. CHETN-VI-45, 2016) and using wave data at WIS 63141 & 63142)
Smooth parameter = 11
No regional contour
Boundary Conditions: Moving bc at the north end of Brigantine; no moving bc at the south end of Absecon Island)
Calibrated Model Parameters:
K_1 = 0.25; K_2 = 0.16
No cross-shore transport included.
Dredging: Actual volumes were included in the IRM model

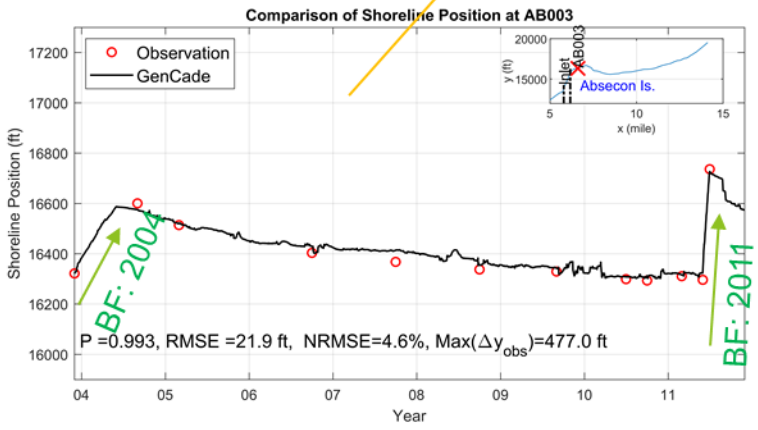
Calibrated Model Results: Shoreline Evolution pre-Sill (2003-2011)

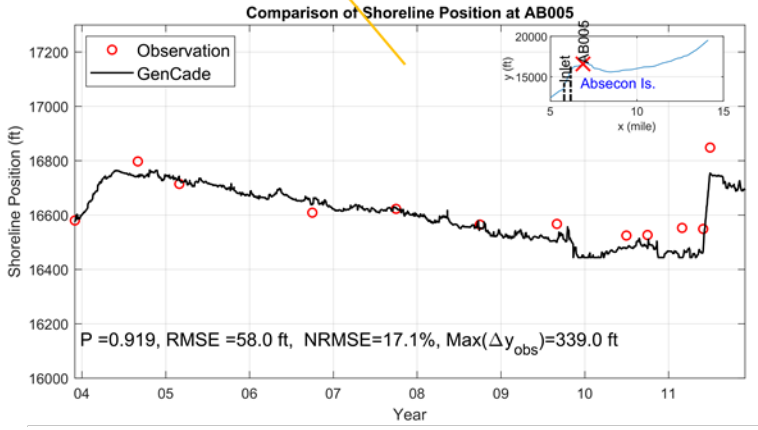


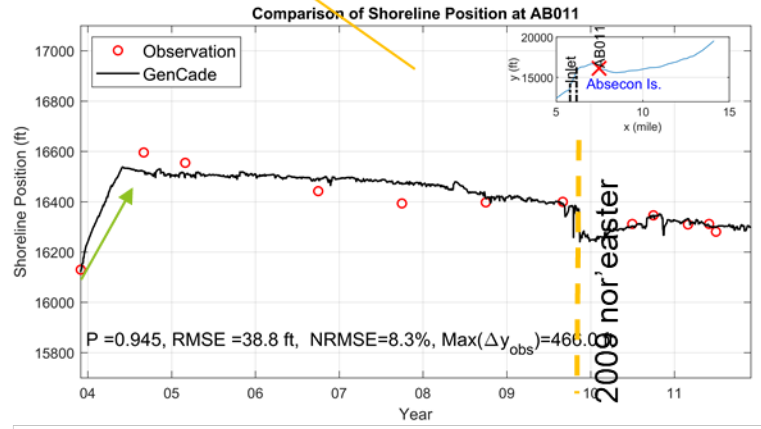




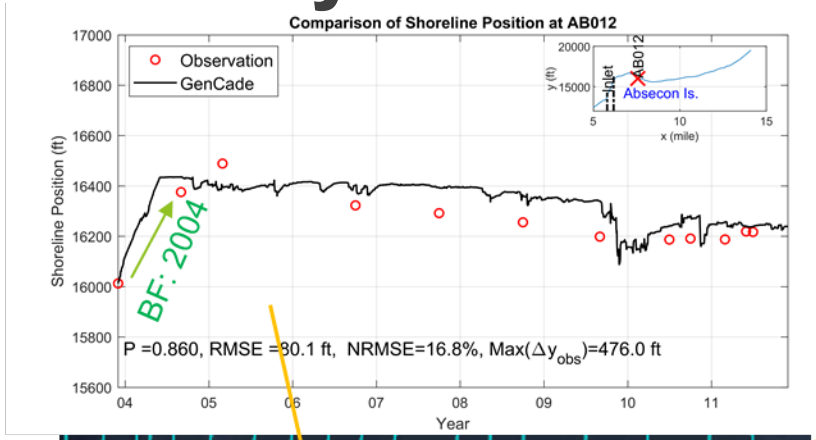


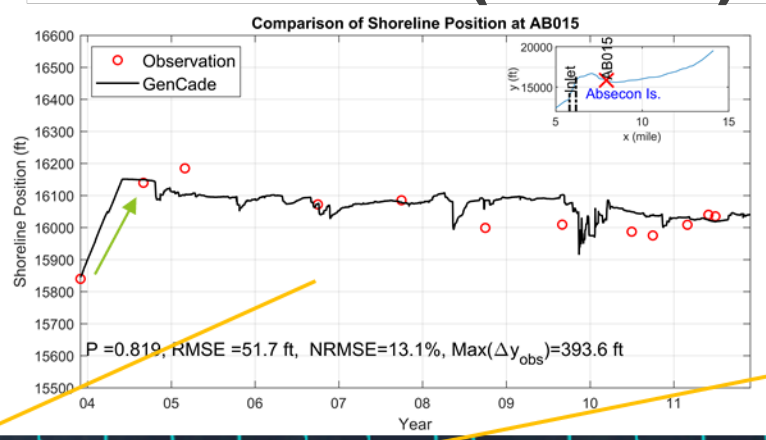


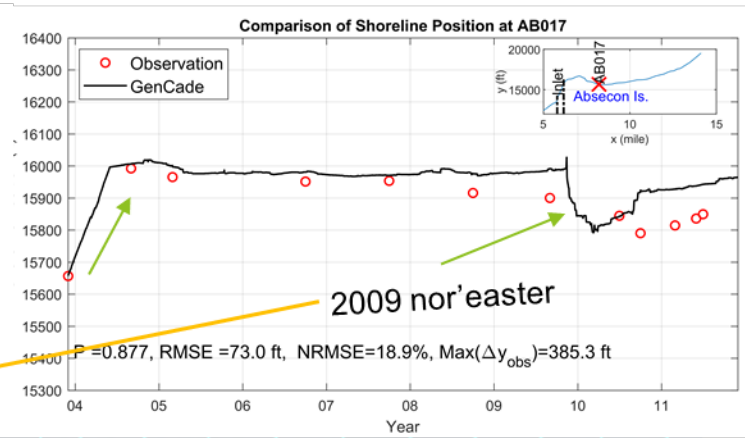


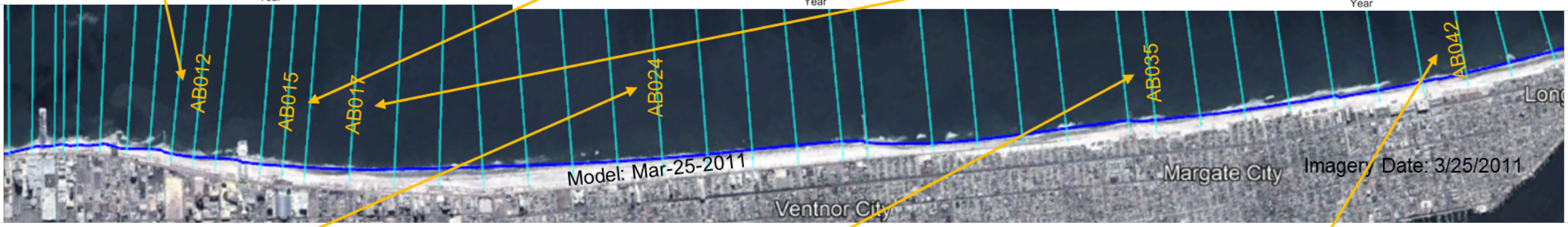


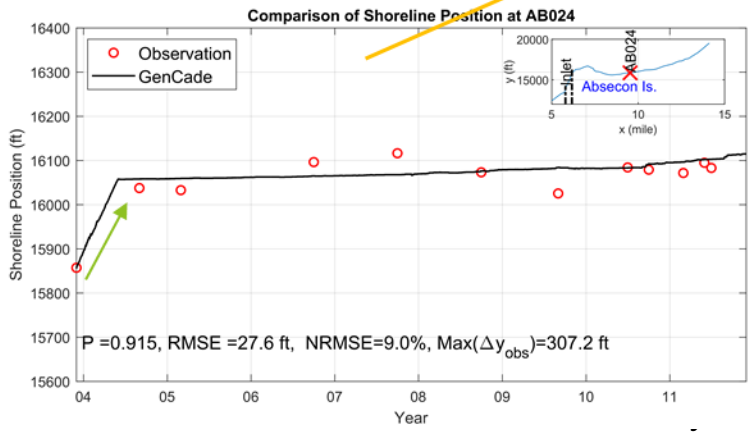
History of Shoreline Positions (>EHS)

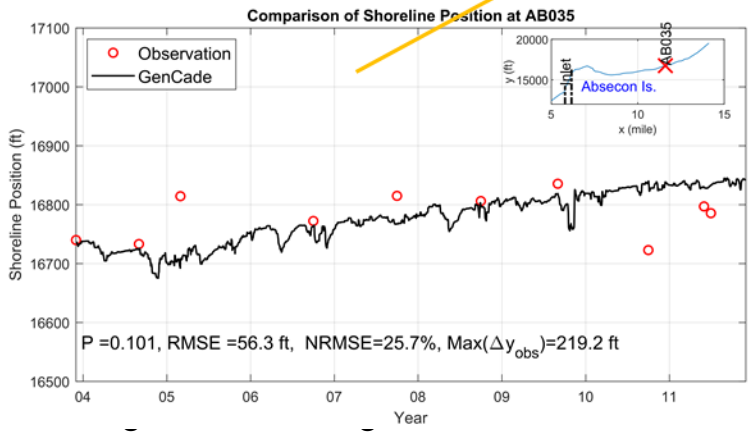


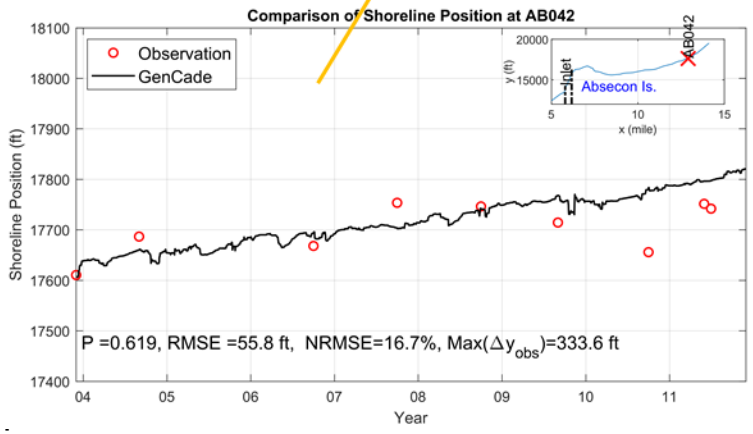






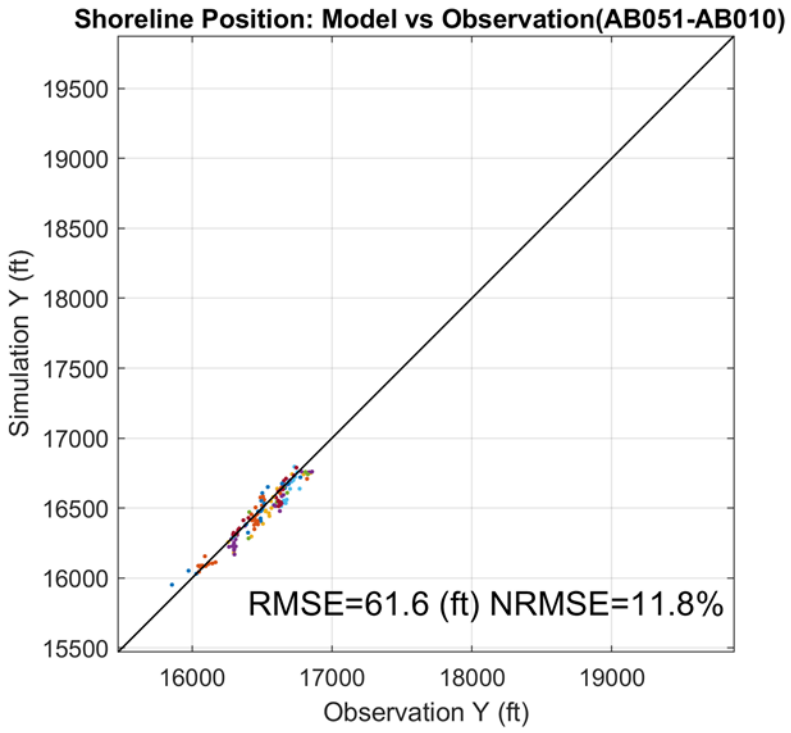






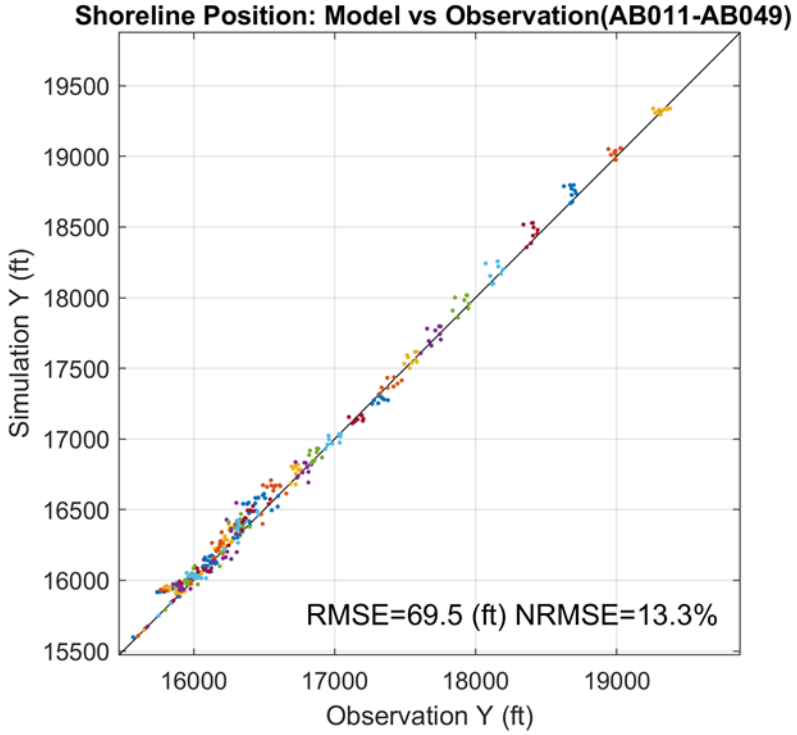
Q-Q Plots of Shoreline Positons (y) (Calibration: 2003-2011)

(1) EHS



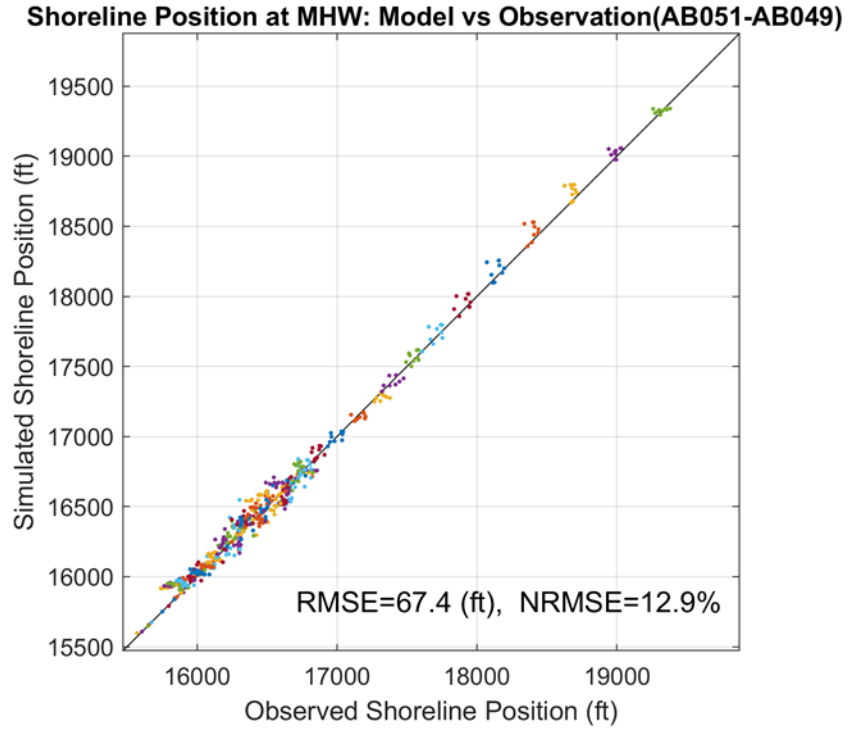
Number of Data (N)=143

(2) Beyond EHS



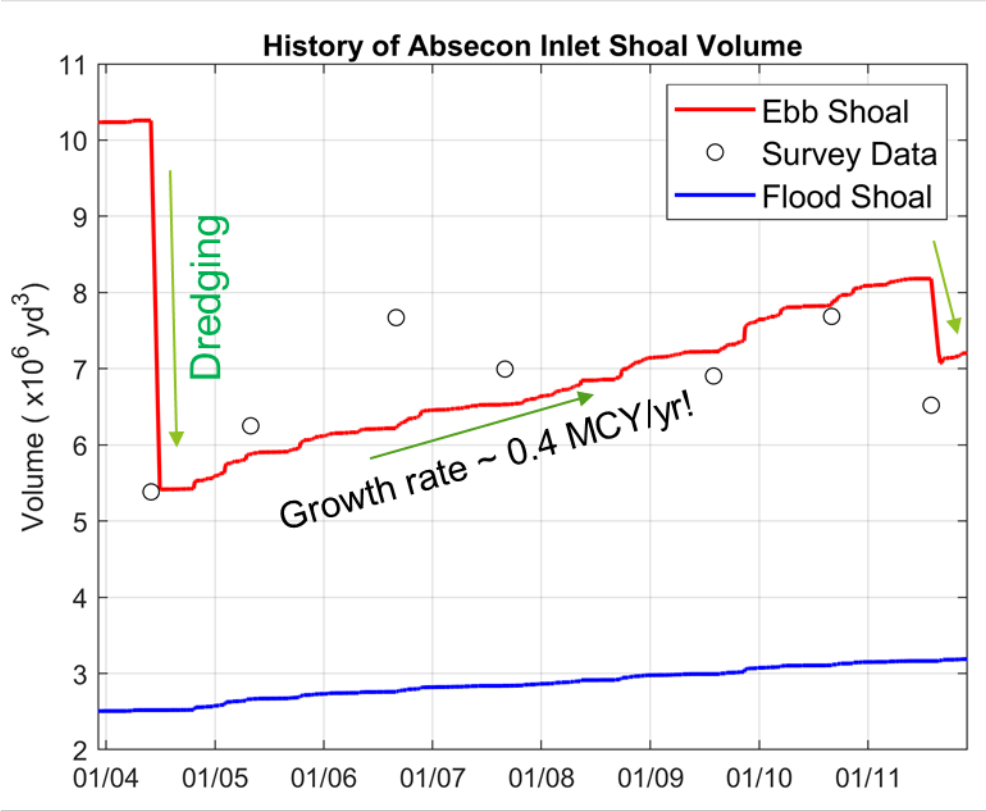
Number of Data (N)=414

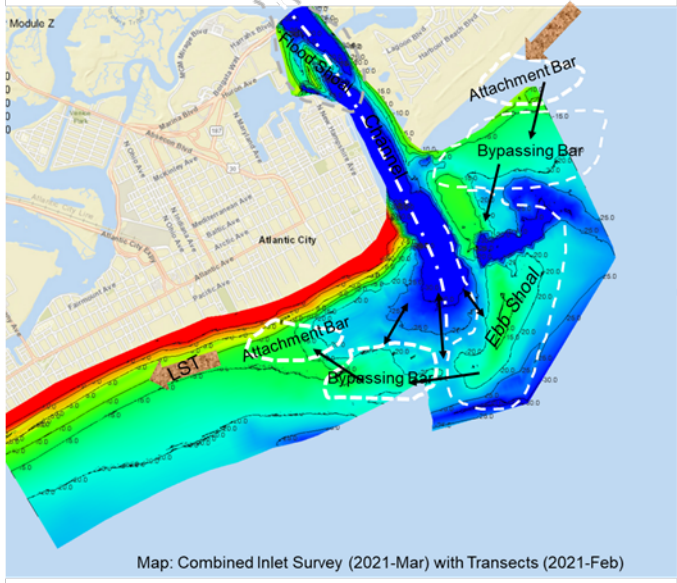
(3) All Lines in Absecon Island

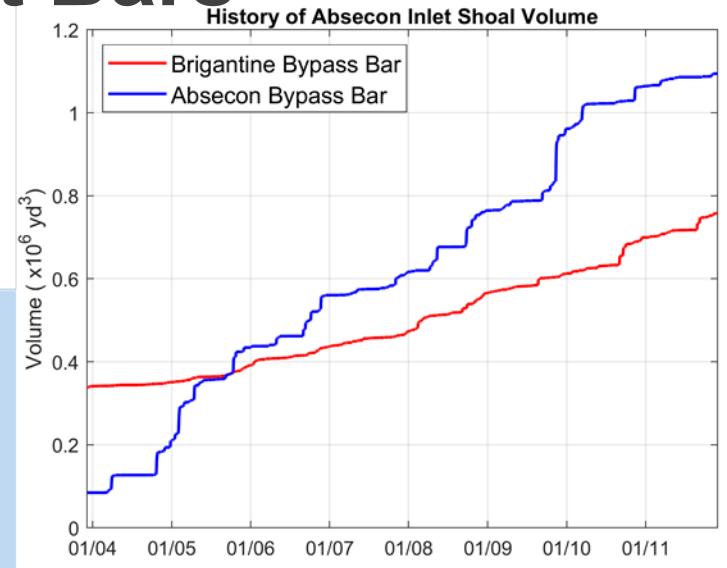


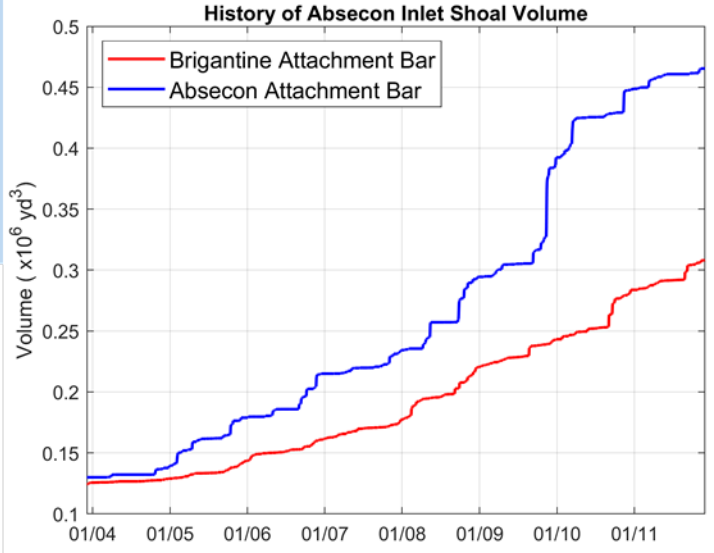
Number of Data (N)=557

Evolution of Inlet Shoals and Attachment Bars









Model Validation (2011-2013-2019)

Objectives:

(1) to validate the GenCade Absecon Inlet model using the calibrated parameters

(2) to examine the effect of Revel Sill (detached breakwater),

(3) to adjust permeability of groins due to structure rehab/extension) , and

(3) to validate the IRM model for simulation of shoal evolution and sediment bypassing by the inlet.

Table 1. Absecon Island Beachfill Placement since Initial Construction in 2003 (NAP Report)

Beachfill Dates	Atlantic City	Ventnor	Margate	Longport	Total	Notes
Dec 2003-June 2004	3,600,000	1,260,000	0	0	4,860,000	
Mar-July 2011	1,003,000	0	0	0	1,003,000	Vermont to North Carolina Aves. in AC
Feb -Jun 2012	955,000	375,000	0	0	1,330,000	
Jun to Dec 2013	791,000	530,000	0	0	1,321,000	
May-Aug 2017	1,249,000	353,000	1,000,000	867,000	3,469,000	
Dec 2020 - Feb 2021	1,296,000	550,000	85,000	141,000	2,072,000	
Dec 2003 - Feb 2021	8,894,000	3,068,000	1,085,000	1,008,000	14,055,000	

Table 2. Brigantine Island Beachfill Placement since Initial Construction in 2006 (NAP Report)

Construction	Date Completed	Pay Quantity, cy
Initial (including 1st periodic renourishment)	Feb 2006	671,000
FCCE emergency rehab	Dec 2011	94,000
2nd periodic renourishment	Dec 2012	500,000
FCCE restoration ("repair/restore" project Hurricane Sandy)	Jul 2013	427,000
3rd periodic renourishment and FCCE restoration	Apr 2018	755,000

Conditions and Values:

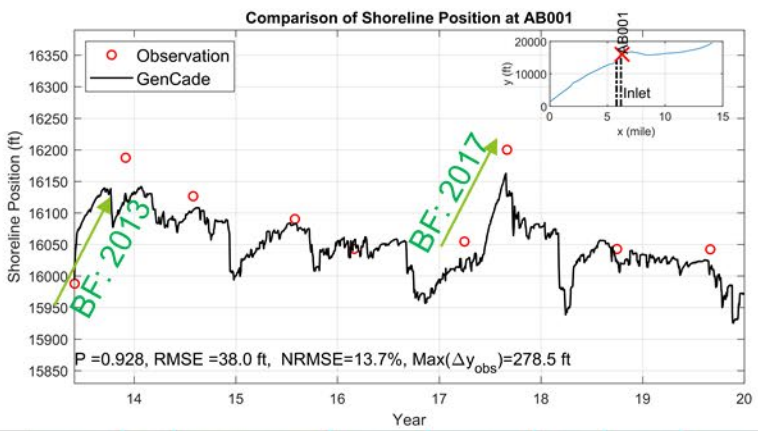
Computational Period:
pre-sill: 2 years, 2011/06/01 0:00 - 2013/06/01 0:00
post-sill: 6.5 years, 2013/06/01 0:00-2020/01/01 0:00
Measured Initial Shorelines: 2011-Jun for pre-sill, 2013-Jun for post-sill

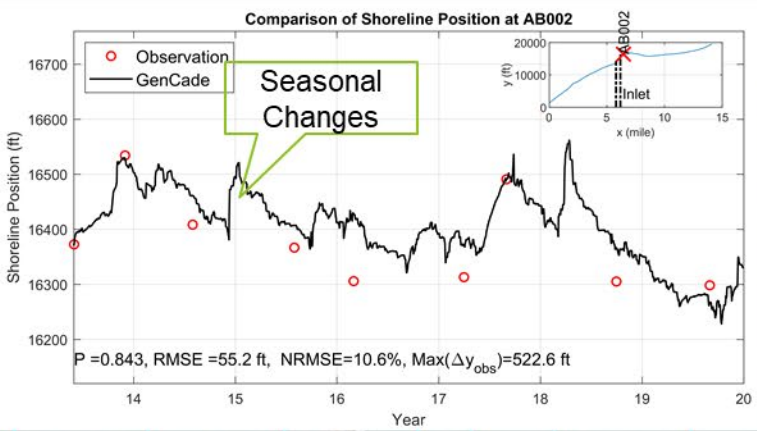
Including beach construction projects (2003-2011):
Absecon: 2011~ 2017
Brigantine: 2011 ~ 2018

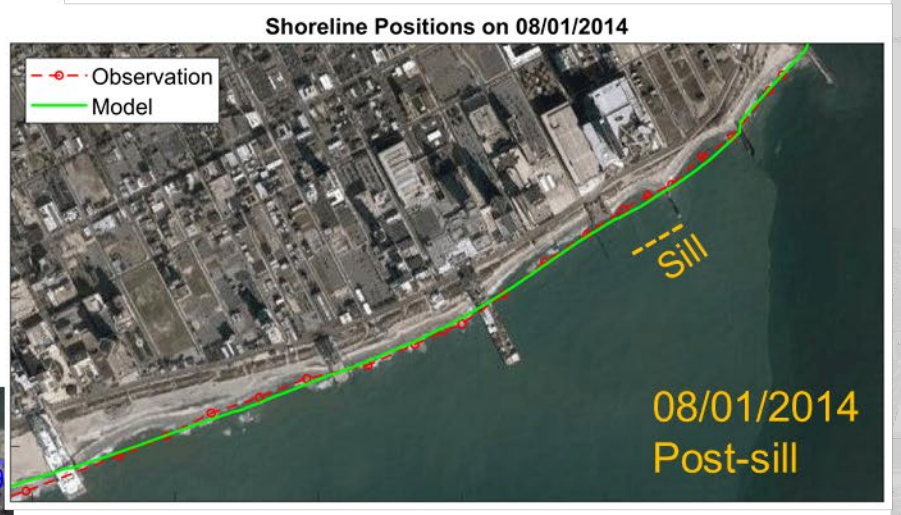
Offshore Waves: WIS 62141 (BI07-AB017) WIS 63142 (AB018-049)
Time step (Δt) = 90 seconds
Grid Size (Δx) = 60 ft
Grain size (d_{50}) = 0.25 mm
Berm Height (D_b) = 5.68 ft (above MHW, or 7.25 ft + NAVD88)
(*Based on beachfill template)
Closure depth (D_c) = 20.1 ft on Brigantine, 26.51 ft on Absecon
(*based on estimates by (Brutsche et al. CHETN-VI-45, 2016) and using wave data at WIS 63141 & 63142)
Smooth parameter = 11
No regional contour
Boundary Conditions: Moving bc at the north end of Brigantine; no moving bc at the south end of Absecon Island)
Calibrated Model Parameters:
K_1 = 0.25; K_2 = 0.16
No cross-shore transport included.

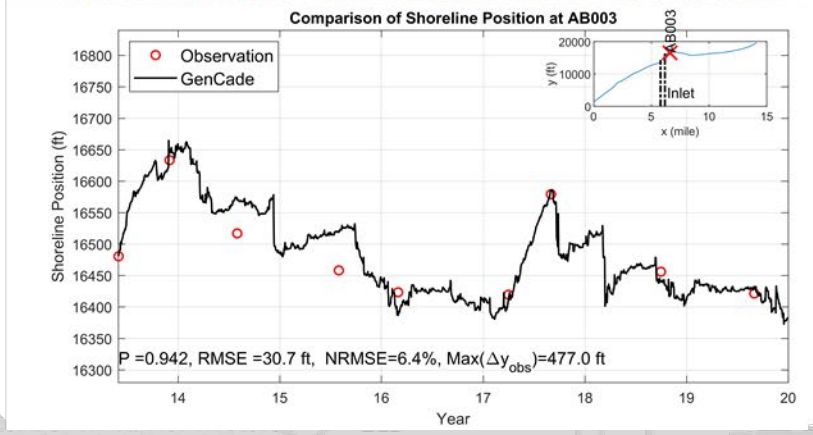
Permeability of Structures: Only those with extension were adjusted
Revel Sill: Wave transmission calibrated: k_t=0.92; dimension and depth were based on design layout
Dredging: Actual volumes were included in the IRM model.

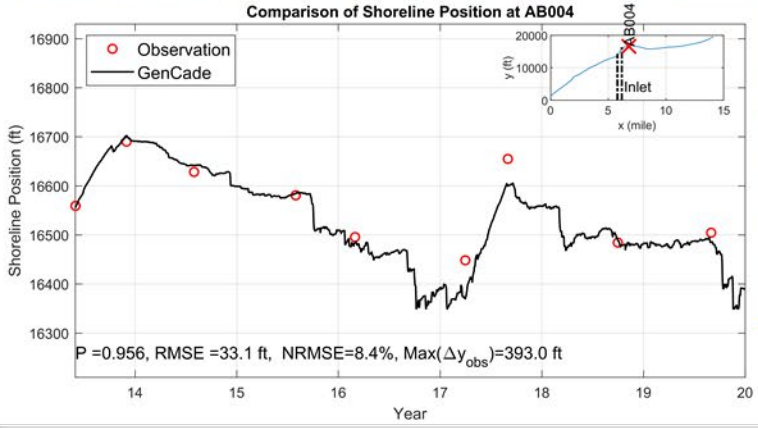
Validation Results: History of Shoreline Changes on EHS





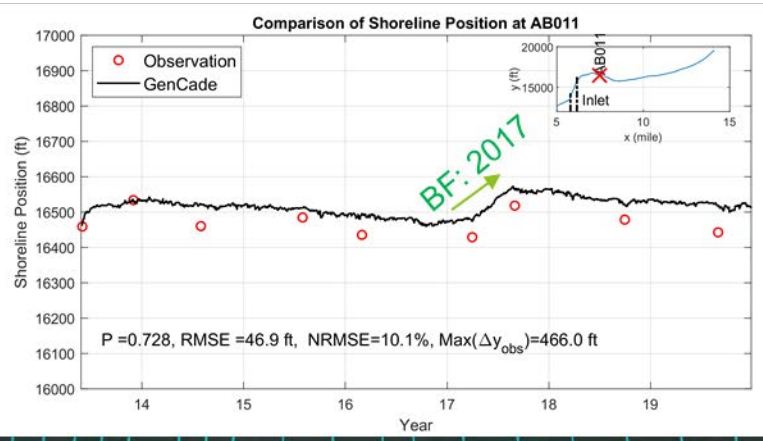


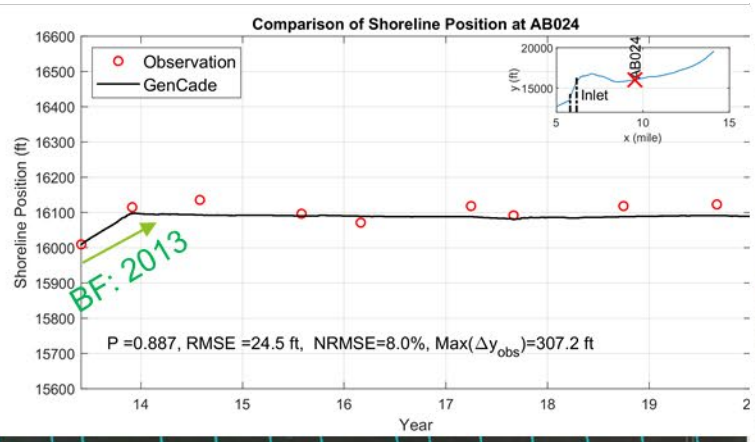


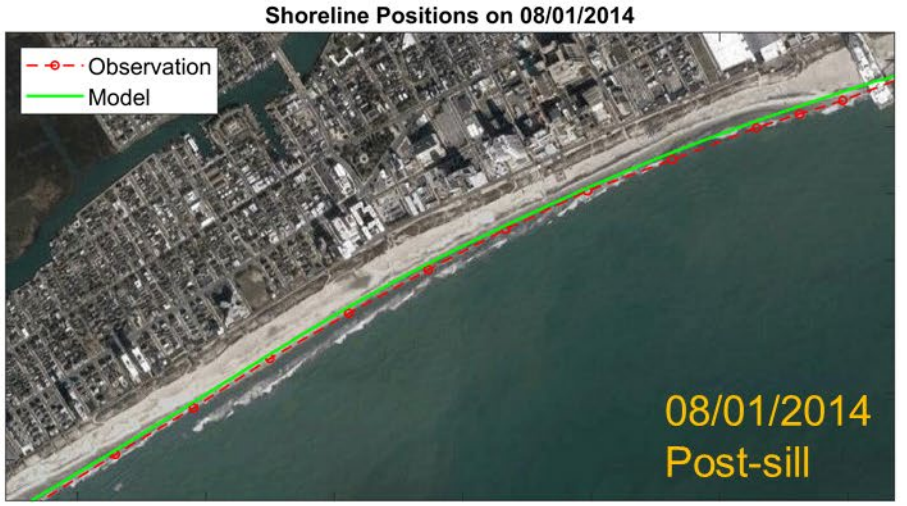


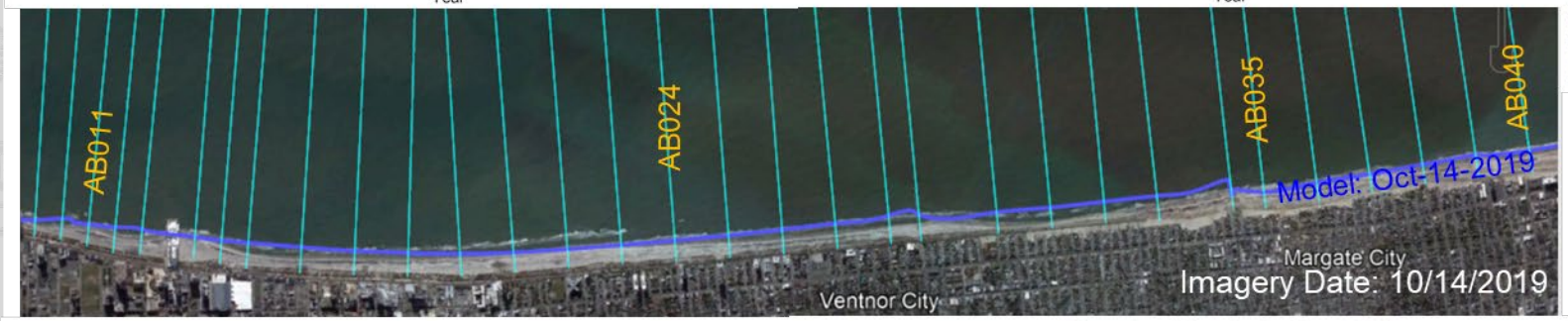
pment Center

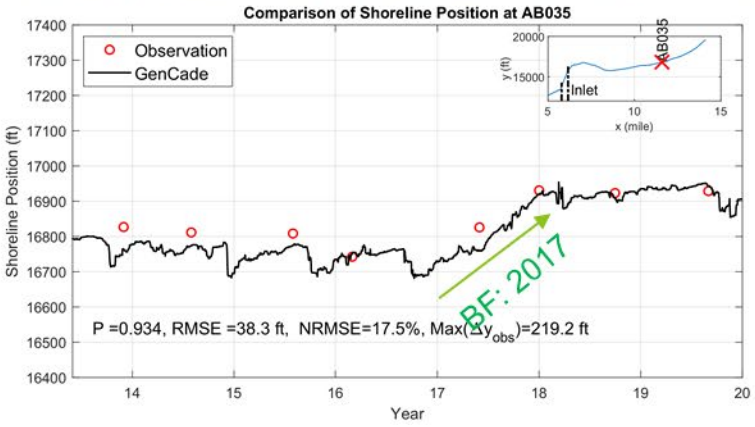
History of Shorelines beyond EHS (Validation: 2013-2019)

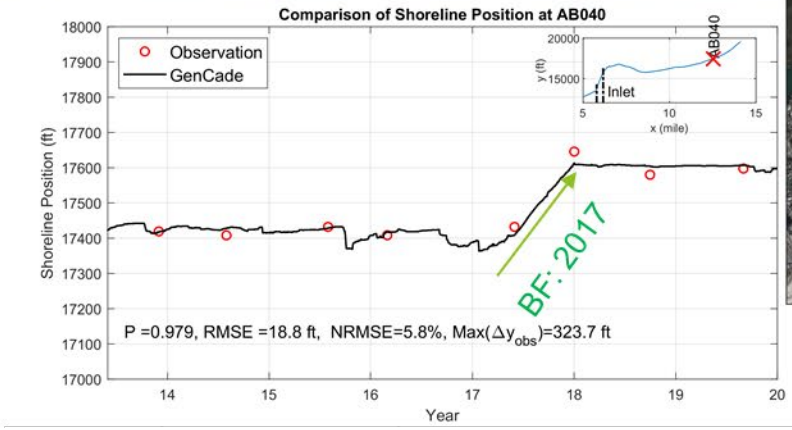






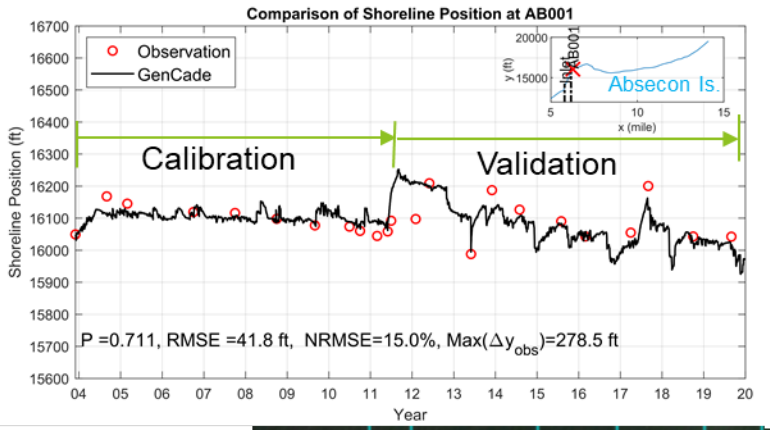


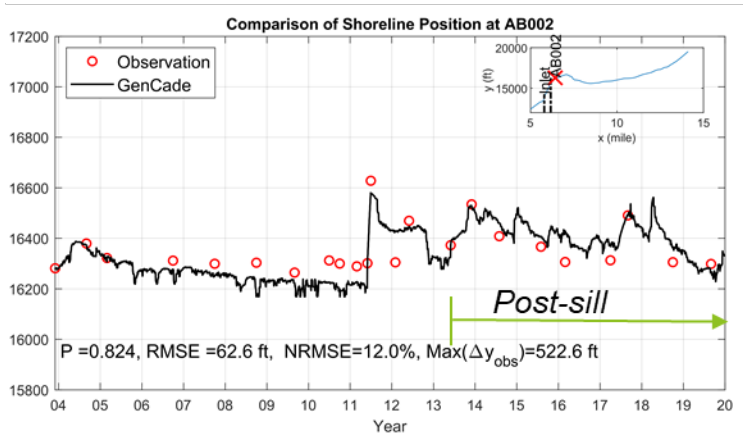


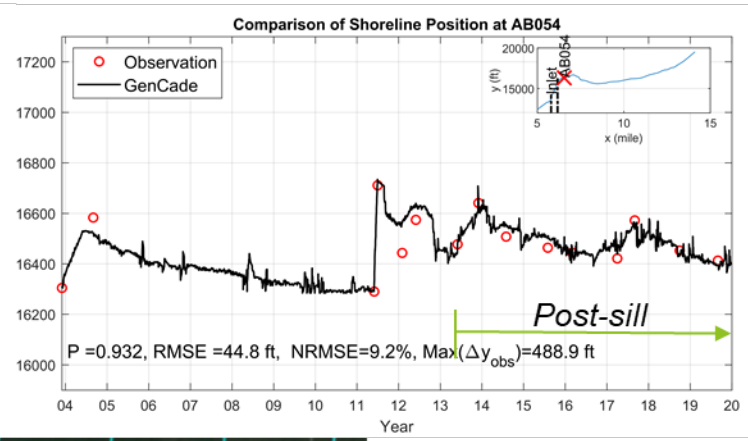


pment Center

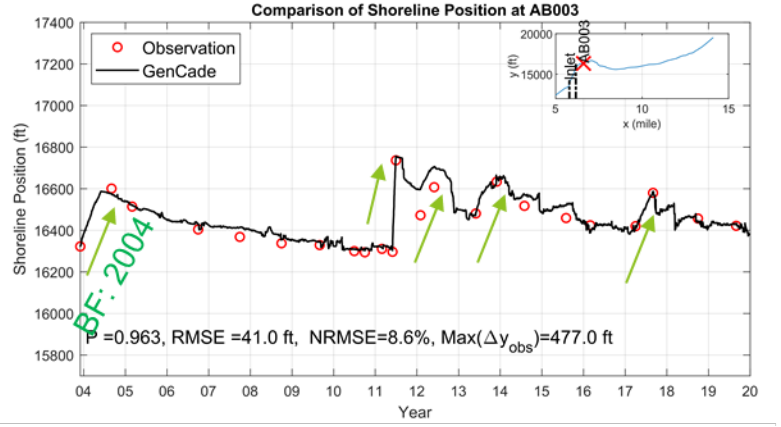
All 16-Year Simulation Results: Calibration + Validation (2003-2020)

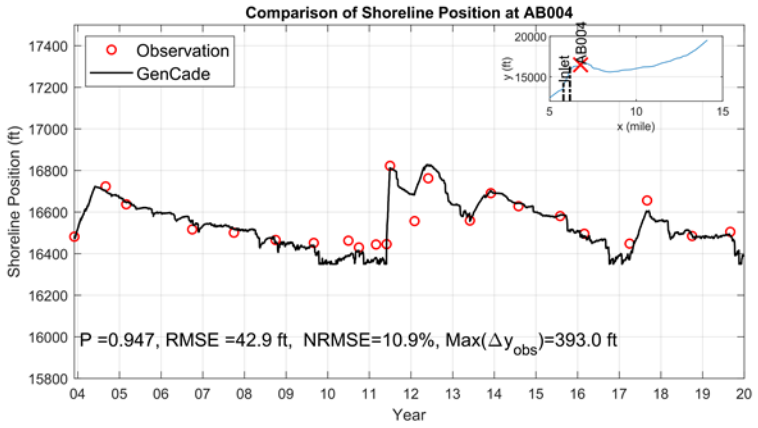


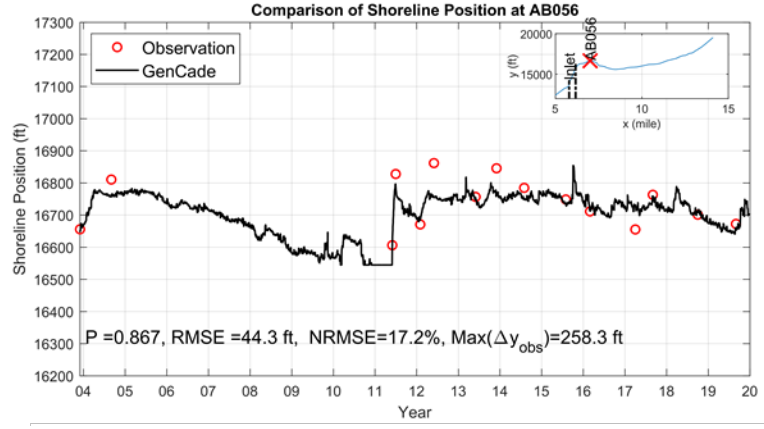




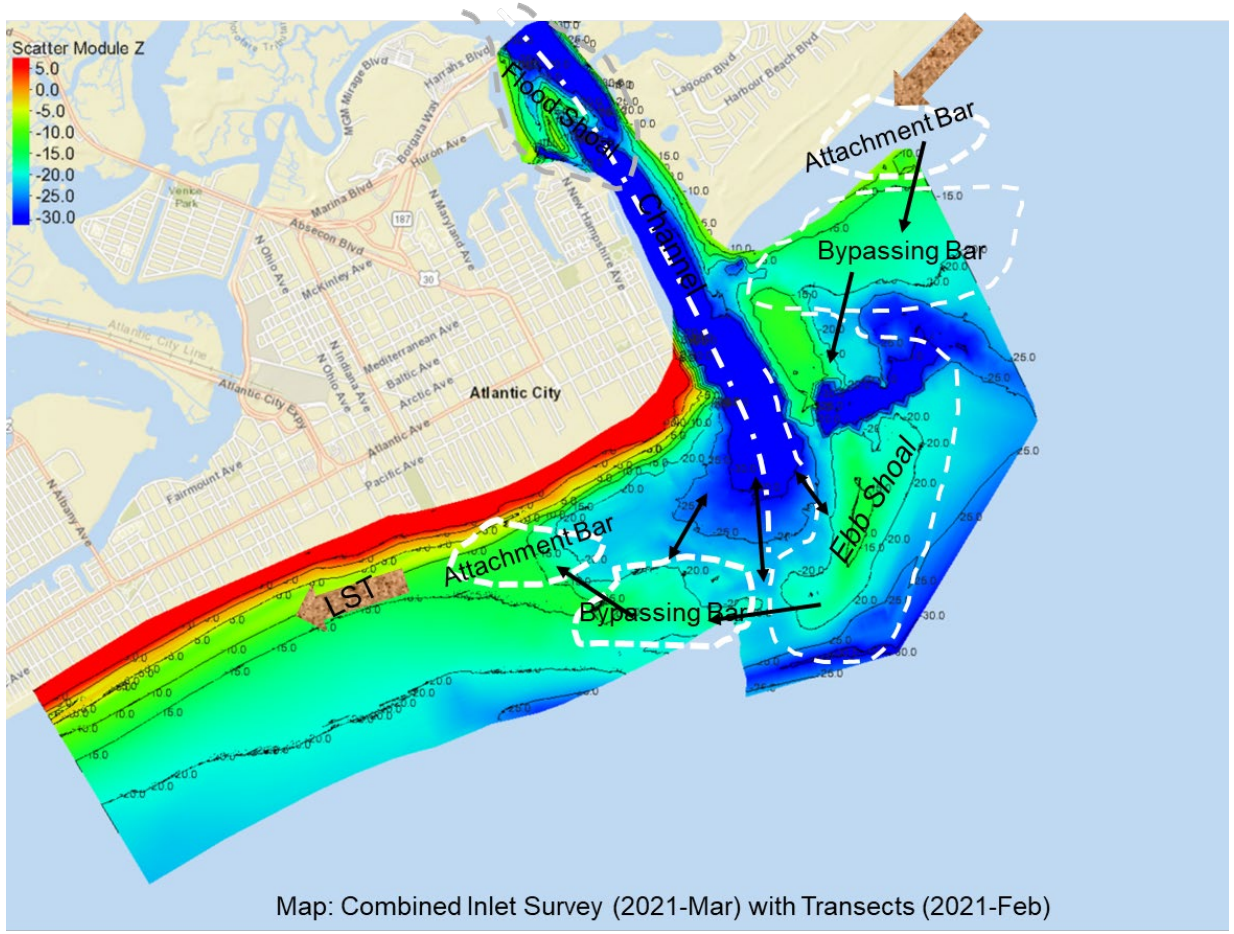
EHS



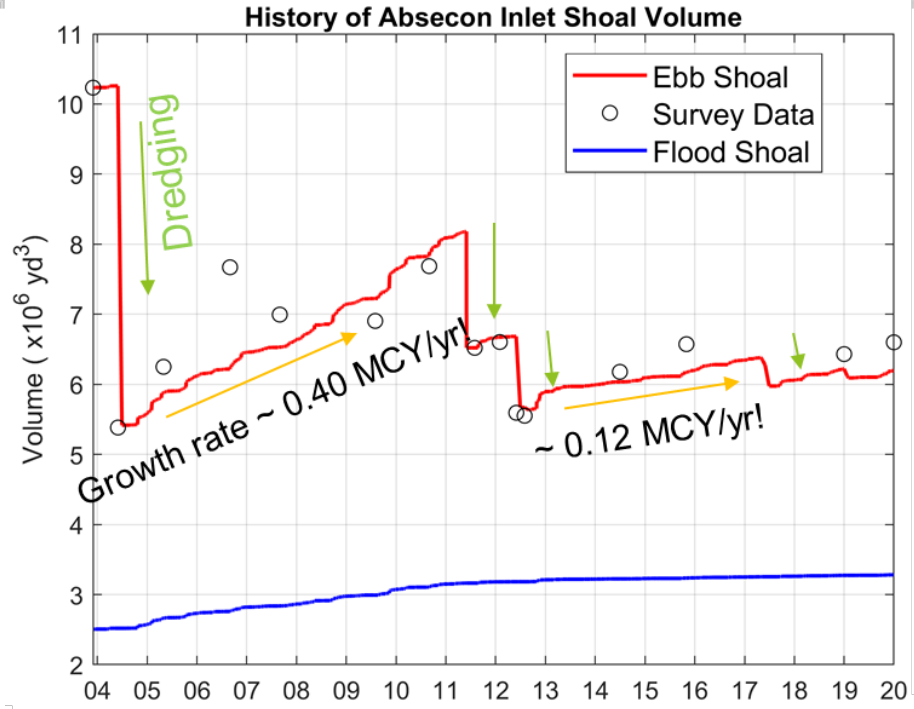


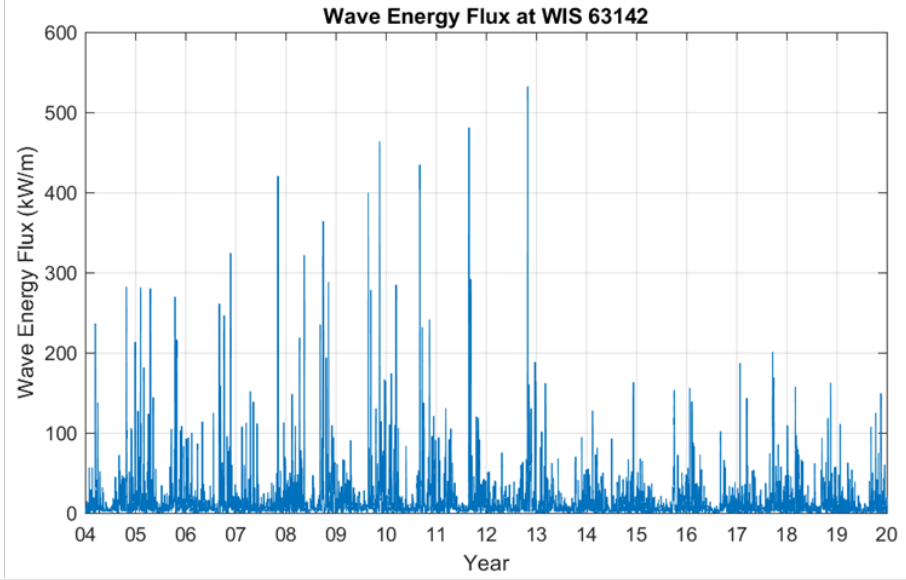


Volume Changes of Shoals and Wave Energy Flux (2003-2020)

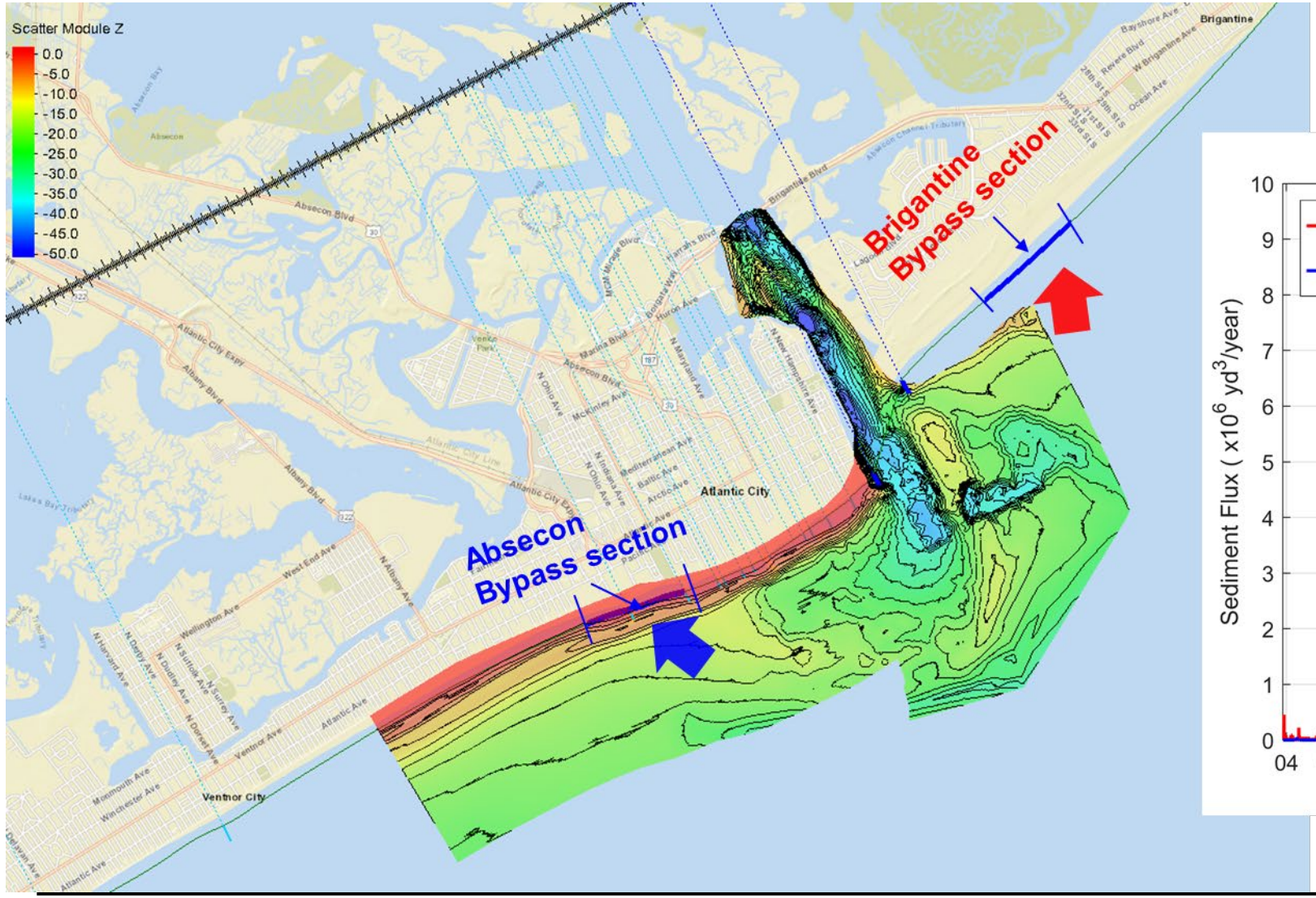


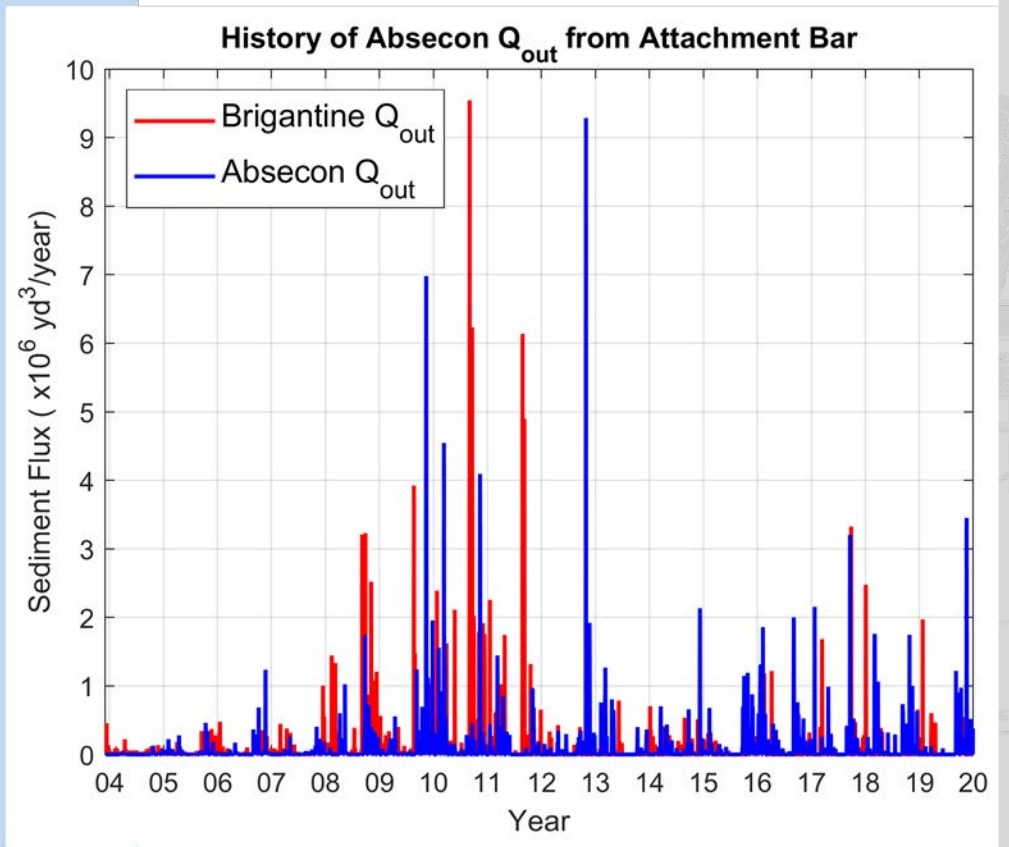
Map: Combined Inlet Survey (2021-Mar) with Transects (2021-Feb)



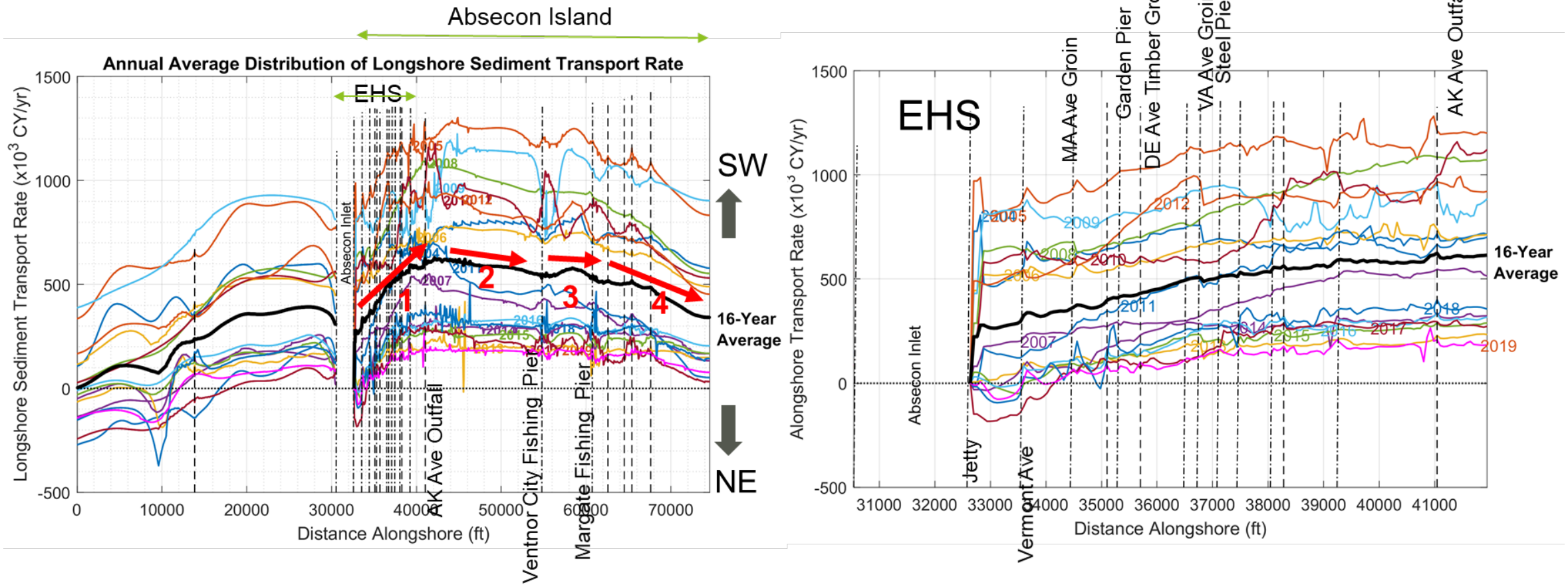


Inlet Bypass Estimated by IRM model (2003-2020)





Annual Average LSTR Distribution – Long-Term Trend



- Trend of Shoreline Change on Absecon Island: 1 (EHS) – erosive; 2- accretive; 3 – erosive/accretive; 4 - accretive (erosive)
- Ranks of Annual LSTR on EHS:
  2005, 2012, 2009, 2008, 2004, 2010, 2006 < 16-year average < 2011, 2007, 2014, 2016, 2013, 2018, 2015, 2017, 2019

Remarks

- Long-term and regional-scale shoreline evolution can be simulated by 1-D shoreline model (GenCade) driven by longshore sediment transport and sediment bypassing through inlet.
- The empirical parametric Inlet Reservoir Model provides a reasonable estimation of inlet morphological changes of shoals and bars. But the accuracy of volume changes by IRM depends on available hydro survey data.
- Impacts of dredging/mining and bypassing operation can be simulated quite well. It demonstrates the model has capability to help designing and planning dredging operation at sand borrow sites (shoal or bar).
- The model is able to simulate the effects of complex coastal structures and beach fill (nourishment) on longshore sediment transport and shoreline change.
- GenCade can provides a quick prediction of long-term and regional shoreline evolution and inlet morphology volumetric changes.
- Limitations: Dynamic changes (shape and location) of shoals and bars, changes of sediment pathways, etc.

Thank you for your attention!

Yan.Ding@usace.army.mil

GenCade model:

https://cirp.usace.army.mil/products/gencade.php

User manual, technical reports, etc:

https://cirp.usace.army.mil/pubs/