ERDC/CHL TR-21-1

Coastal and Hydraulics Laboratory

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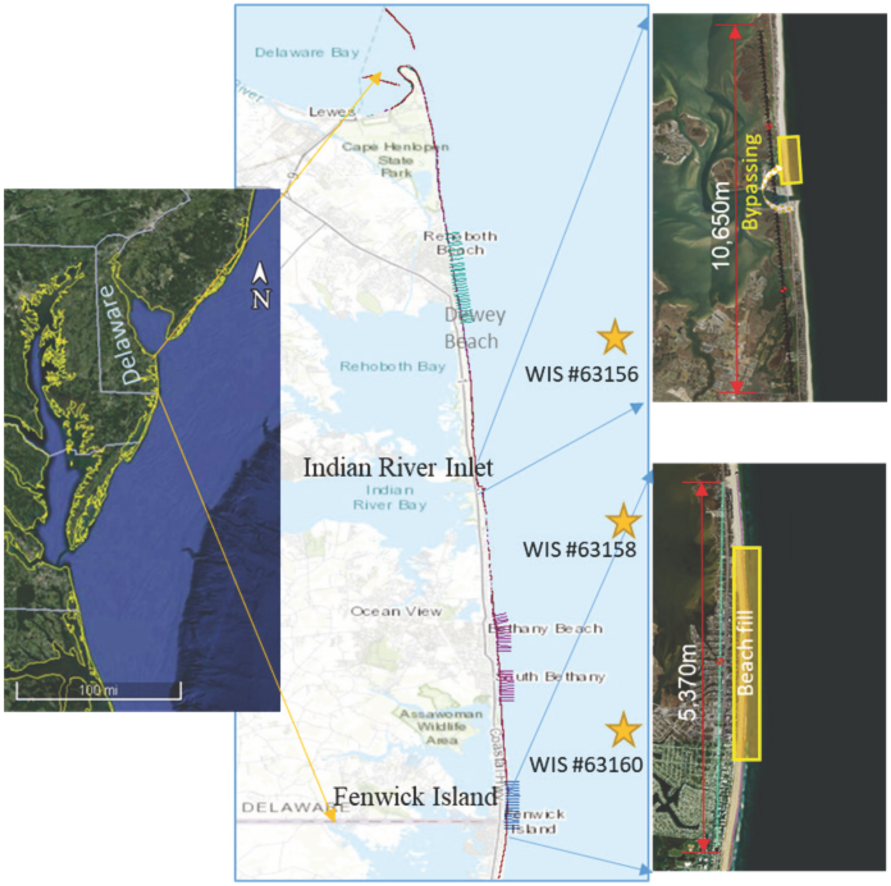
January 2021



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Yan Ding, Sung-Chan Kim, Rusty L. Permenter, Richard B. Styles

Coastal and Hydraulics Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Jeffrey A. Gebert

US Army Corps of Engineers, Philadelphia District (NAP)
Philadelphia, PA 19107

Final report

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Coastal Inlets Research Program
Coastal and Hydraulics Laboratory
US Army Engineer Research and Development Center
Vicksburg, MS 39180-6199

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Abstract

This technical report presents two applications of the GenCade model to simulate long-term shoreline evolution along the Delaware Coast driven by waves, inlet sediment transport, and longshore sediment transport. The simulations also include coastal protection practices such as periodic beach fills, post-storm nourishment, and sand bypassing. Two site-specific GenCade models were developed: one is for the coasts adjacent to the Indian River Inlet (IRI) and another is for Fenwick Island. In the first model, the sediment exchanges among the shoals and bars of the inlet were simulated by the Inlet Reservoir Model (IRM) in the GenCade. An inlet sediment transfer factor (γ) was derived from the IRM to quantify the capability of inlet sediment bypassing, measured by a rate of longshore sediments transferred across an inlet from the updrift side to the downdrift side. The second model for the Fenwick Island coast was validated by simulating an 11-year-long shoreline evolution driven by longshore sediment transport and periodic beach fills. Validation of the two models was achieved through evaluating statistical errors of simulations. The effects of the sand bypassing operation across the IRI and the beach fills in Fenwick Island were examined by comparing simulation results with and without those protection practices. Results of the study will benefit planning and management of coastal sediments at the sites.

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Preface

This study was conducted for the US Army Corps of Engineers, National Regional Sediment Management Program, US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), and supported from the GenCade model development team under the Coastal Inlets Research Program, under Funding Account Code 237H7F, AMSCO Code 060000, “Simulation of Shoreline Changes in the Delaware Coast.”

The work was performed by the Coastal Processes Branch of the Flood and Storm Protection Division, ERDC-CHL. The general administrative supervision was provided by Ms. Ashley E. Frey, Chief, Coastal Processes Branch, and Dr. Cary Talbot, Chief, Flood and Storm Protection Division. At the time the study was completed, Dr. Julie D. Rosati was the Technical Director for Flood and Risk Management; The Deputy Director of ERDC-CHL was Mr. Jeffrey Eckstein; and the Director was Dr. Ty V. Wamsley.

Sincere appreciation is expressed to Mr. Jesse Hayden (Delaware Department of Natural Resources and Environmental Control) and Ms. Eve Eisemann (CHL) for providing survey data of beach profiles and zero contour maps of LIDAR data and to Mr. Douglas R. Krafft and Ms. Sally (Catie) Dillon for their valuable review comments.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Along the relatively short and straight Atlantic coast of Delaware, shoreline configurations are largely determined by antecedent geology and inlet morphology, and variations of shoreline are influenced by episodic events (e.g., coastal storms) and erosion protection practices (e.g., beach nourishment) (DNREC 2018). Studies of the Delaware shoreline evolution in the past have revealed that the long-term trend of the shoreline is erosional, with fluctuating erosional/accretional stages with changes in environmental parameters (e.g., Galgano 2008; Puleo 2010). Erosion protection practices play an important role in shoreline stability as well as evolution of shoreline/beach positions and shapes.

There are four major shore protection projects along the Delaware coastline: Rehoboth Beach, Dewey Beach, Bethany/South Bethany, and Fenwick Island (Figure 1). Ocean City, MD, also conducts regular shoreline nourishments. Indian River Inlet navigation and sandy bypass project has been a focus of many sand bypassing and dredging studies (e.g., Keshtpoor et al. 2013; USACE-NAP 2018). Delaware kept records of the history of state-led beach fills since the 1950s and federal beach fill projects since 2004. In addition, regular transects of the Delaware shoreline exist from 2004 with wave observation data from the US Army Corps of Engineers (USACE) at Bethany, Dewey, and Ocean City (USACE 1996). Beach profiles and nearshore waves are two critical variables for predicting shoreline evolutions. Studies by Puleo (2010) provide a 20-year mean alongshore sediment transport and the location of a nodal point along the Delaware coastline by using the CERC (Coastal Engineering Research Center) formula. However, for the purpose of quantitative management of sediments and shoreline erosion, it is essential to develop a site-specific shoreline simulation model to predict long-term shoreline changes along the Delaware coast by considering wave dynamics and coastal protection practices such as beach fills, sand nourishment, and sand bypassing projects.

1.2 Objective

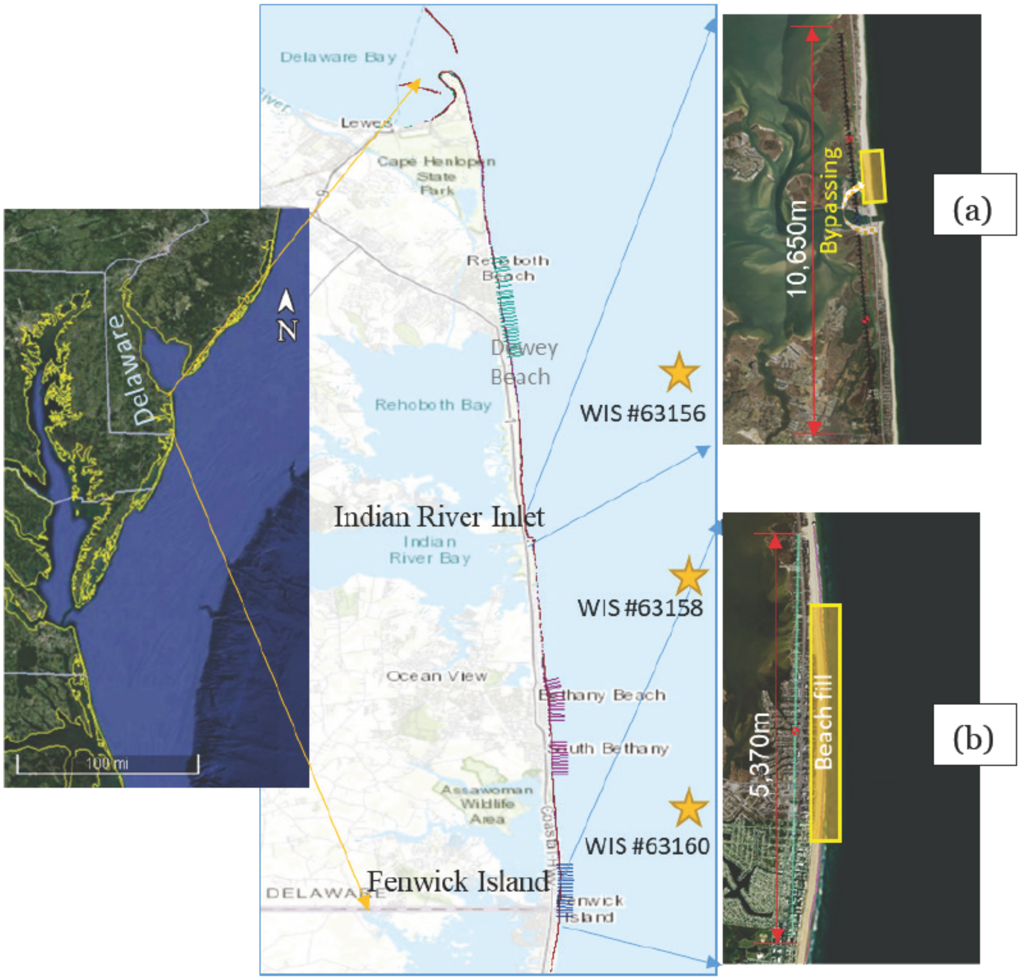
The main goal of the study is to apply the GenCade model to reproduce the historical shoreline evolution along the Delaware coast driven by environmental factors such as inlet sediment transport, offshore waves, and longshore sediment transport. The simulations also include coastal erosion protective measures such as periodic beach fills, post-storm nourishment, and sand bypassing. Validated GenCade models are used for quantifying the effects of the sand bypassing operation across the Indian River Inlet and the beach fills in Fenwick Island. Results of the study will benefit planning and management of coastal sediments at the sites.

1.3 Approach

Two site-specific GenCade shoreline evolution models are developed (Figure 1a and 1b): one is for the coasts adjacent to the Indian River Inlet, and the second is for Fenwick Island. Model validations are performed by evaluating statistic errors of simulated shoreline positions, by comparing with historical shoreline positions. The observation shoreline data are extracted from the beach profiles measured by Delaware Department of Natural Resources and Environmental Control (DNREC) and USACE Philadelphia District (NAP).

Tests of the Inlet Reservoir Model (IRM) in GenCade are needed for estimating sediment exchange between the Indian River inlet and adjacent beaches. The sand bypassing capability of the inlet system is quantified by using a newly defined sediment transport factor to measure the transfer rate of longshore sediment through an inlet from the updrift side to the downdrift side. The effect of the sand bypassing operation is evaluated in the first case of the Indian River Inlet. The impact of periodic beach fills is quantified in the second case on the Fenwick Island coast.

Figure 1. Delaware Coast and two study sites for shoreline evolution modeling: (a) Indian River Inlet (IRI) and its adjacent coasts and (b) Fenwick Island coasts. The color-coded lines perpendicular to the coast indicate survey transects. The three star symbols indicates the Wave Information Studies (WIS) wave buoys (WIS 2019).



2 GenCade and Inlet Reservoir Model (IRM)

2.1 GenCade: Shoreline evolution model

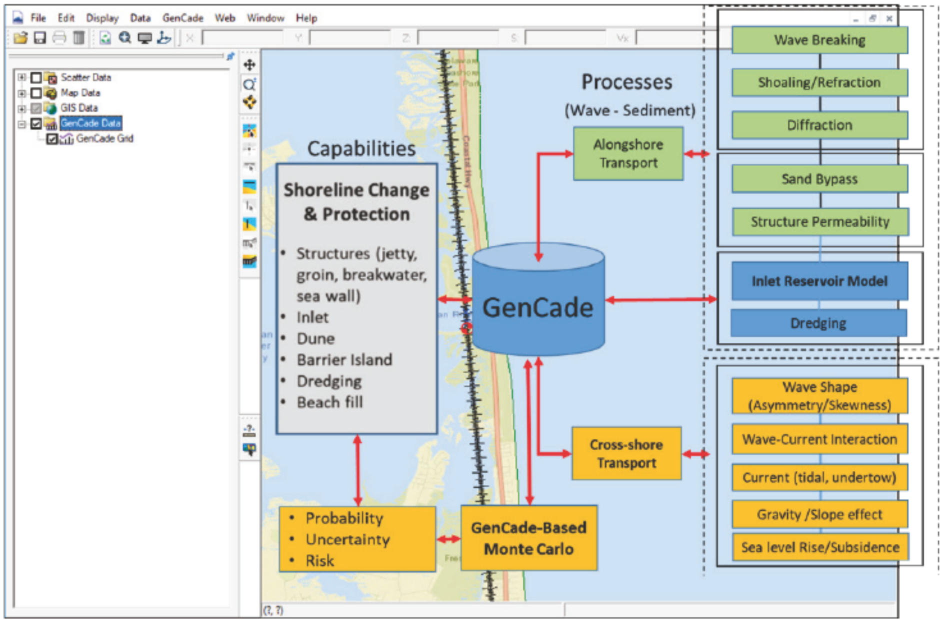
GenCade is a USACE shoreline evolution model that simulates long-term shoreline change on coasts with structures such as breakwaters, groins, and jetties and beach fills and nourishment activities (Frey et al. 2012). Shoreline changes in the model are driven by alongshore sediment transport, calculated by the CERC formula, which relates the transport rate to waves and currents in the wave breaking zone. The model includes a module called the IRM (Kraus 2000; Larson et al. 2003, 2006) to simulate the inlet sand bypassing through evolution of sand volume in inlet morphological elements (flood/ebb shoals, bypassing/attachment bars, and the inlet channel). As a result, GenCade is capable of simulating shoreline variations across inlets and structures and enables the assessment of coastal protection project performance for coastal restoration and stabilization. GenCade is run within the Surface-Water Modeling System (SMS) versions 11.1 and higher.

GenCade has been widely used in coastal engineering projects for shoreline erosion protection, coastal sediment management, and coastal hazard management (e.g., Hanson et al. 2011; Milligan and Hardaway 2014; Frey 2015). Recent development and validation of the model has provided new simulation capabilities including cross-shore sediment transport processes, sea level rise, and subsidence, as well as probabilistic shoreline change prediction (Ding et al. 2018, 2019, 2020). By including the shoreline changes due to cross-shore transport, sea level rise, and land subsidence, the updated shoreline evolution equation in GenCade is given as follows (Frey et al. 2012; Ding et al. 2020):

$$\frac{\partial y}{\partial t}=\frac{1}{D_S}\left(-\frac{\partial Q_l}{\partial x}+q_s+\phi\right)-\frac{R+S}{\tan\beta} \tag{1}$$

where y = the cross-shore coordinate and represents the shoreline position, t = time, x = the alongshore coordinate, Q_l = the longshore transport rate, D_s = the total closure depth, q_s = line source or sink of sediment, ϕ = the cross-shore transport rate (positive sign for onshore transport, negative for offshore), R = sea level rise rate, S = subsidence, $\tan\beta$ =an average beach slope (=D_s/W_* where W_* = width of the active profile (which is approximately the width of longshore sediment transport zone). Equation (1) represents a new governing equation for GenCade to simulate shoreline evolution driven by long- and cross-shore transport, sea level change, and land subsidence. The shoreline retreat rate due to sea level rise and subsidence is based on the assumption of the equilibrium beach profile (Bruun 1962; Rosati et al. 2013). For longshore transport, the CERC formula (Frey et al. 2012) is used to estimate Q_l. Cross-shore sediment transport plays an important role in driving beach evolution including shoreline movement and bar migration. A semi-empirical model for estimating the phase-averaged net cross-shore transport rate has been implemented into GenCade and was validated by simulating shoreline changes in a barred beach (Ding et al. 2019, 2020). Figure 2 illustrates the physical processes and simulation capabilities of GenCade. The capabilities and processes for cross-shore sediment transport and the Monte-Carlo simulation are recently developed. One may refer to Ding et al. (2018, 2020) for the details of those new simulation capabilities.

Figure 2. Capabilities and processes in GenCade. Boxes filled with an orange color are newly implemented processes or capabilities. The other boxes are the existing capabilities and processes. The background image is the GenCade model in the SMS graphical user interface.

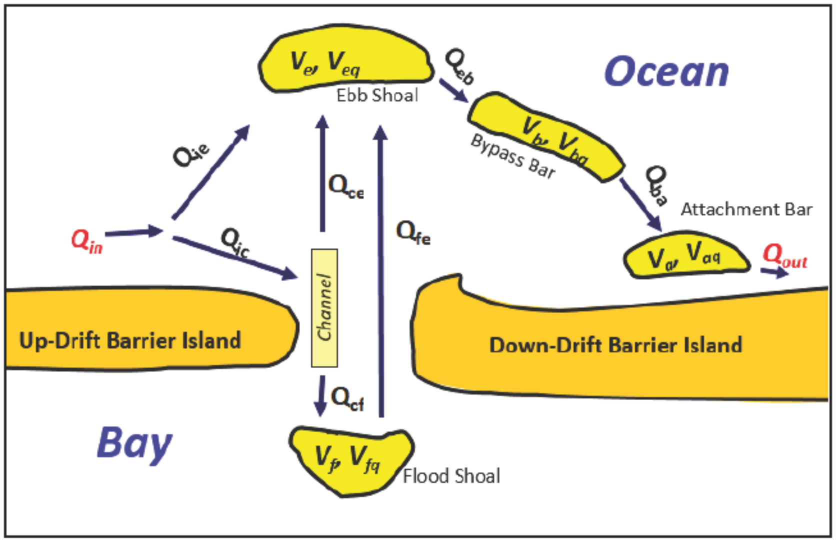


2.2 Inlet Reservoir Model (IRM)

Kraus (2000) developed the IRM and Larson et al. (2003, 2006) implemented it into GenCade to simulate the inlet sediment bypassing from the updrift barrier to the downdrift barrier and between flood and ebb shoals, based on an assumption of equilibrium shoal volumes.

Figure 3 illustrates six morphological elements: flood and ebb shoals, a bypass bar, and an attachment bar on each side of the inlet, as well as an inlet channel. The same mathematical expressions used in Frey et al. (2012) are adopted here to define the sand volume of each morphological elements and the sediment flux passing from one element to another. For example, given that V_x is the sand volume of a morphological element (shoal or bar), then V_{xq} represents an equilibrium volume of this element. The subscript x is a placeholder for subscripts a (attachment bars), b (bypass bars), e (ebb shoal), or f (flood shoal).

Figure 3. Sediment bypassing and evolution of shoals in the IRM.



Each morphological element is assumed to have a certain equilibrium volume for fixed hydrodynamic and sediment conditions. Starting from the updrift side, the IRM proportionally distributes the updrift alongshore sediment transport flux Q_{in} to the two immediate downdrift elements, ebb and flood shoals. Then the received transport rates of the ebb and flood shoals, Q_{ie} and Q_{ic} are

$$Q_{ie} = \delta Q_{in} \tag{2}$$

$$Q_{ic} = (1-\delta) Q_{in} \tag{3}$$

where the distribution rate δ is determined by the ratio of the current (or actual) total volume of ebb and flood shoals ($V_e + V_f$) to the total equilibrium volume of the two shoals ($V_{eq} + V_{fq}$) (Kraus 2000), i.e.,

$$\delta = \frac{V_e + V_f}{V_{eq} + V_{fq}} \tag{4}$$

Then, Q_{ic} will further be divided into two parts: Q_{ce} and Q_{cf} which go to ebb and flood shoals, respectively:

$$Q_{ce} = \beta Q_{ic},\ Q_{cf} = (1-\beta)Q_{ic} \tag{5}$$

where the distribution rate is given as follows:

$$\beta = \frac{1 - V_e / V_{eq}}{2 - V_e / V_{eq} - V_f / V_{fq}} \tag{6}$$

For each simulation time step (Δt), the flux of sediment from the flood shoal (Q_{fe}) that goes to the ebb shoal is

$$Q_{fe} = \begin{cases} (V_f - V_{fq}) / \Delta t & V_f > V_{fq} \\ 0 & V_f \le V_{fq} \end{cases} \tag{7}$$

Kraus (2000) assumed that the sediment passing through each morphological element is proportional to the ratio between the actual volume and the equilibrium volume for the element. The fluxes (Q_{eb},Q_{ba}, and Q_{out}) of sediment out of the ebb shoal, bypassing bar, and attachment bar are determined by

$$Q_{eb} = \frac{V_e}{V_{eq}}(Q_{ie} + Q_{fe} + Q_{ce}) \tag{8}$$

$$Q_{ba} = \frac{V_b}{V_{bq}} Q_{eb} \tag{9}$$

$$Q_{out} = \frac{V_a}{V_{aq}} Q_{ba} \tag{10}$$

If equilibrium is attained, all sediment entering the particular morphologic element is transferred downstream. By assembling the equations of the transport fluxes (Equations (2), (5), (7), and (8)–(10)), one equation for the relationship between the updrift sediment flux Q_{in} and the received downdrift Q_{out} is derived, i.e.,

$$Q_{out} = \begin{cases} \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} \left[\left(\delta + \beta (1-\delta) \right) \right] Q_{in}, & V_f \le V_{fq} \\ \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} \left[\left(\delta + \beta (1-\delta) \right) + \frac{V_f - V_{fq}}{Q_{in} \Delta t} \right] Q_{in}, & V_f > V_{fq} \end{cases} \tag{11}$$

By defining an inlet sediment transfer factor γ as

$$\gamma = \begin{cases} \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} \left[\left(\delta + \beta (1-\delta) \right) \right], & V_f \le V_{fq} \\ \frac{V_e}{V_{eq}} \frac{V_b}{V_{bq}} \frac{V_a}{V_{aq}} \left[\left(\delta + \beta (1-\delta) \right) + \frac{V_f - V_{fq}}{Q_{in} \Delta t} \right], & V_f > V_{fq} \end{cases} \tag{12}$$

the downdrift flux received from the updrift side of the inlet is proportional to the Q_{in}, i.e.,

$$Q_{out} = \gamma Q_{in} \tag{13}$$

This time-dependent transfer parameter is a function of the actual and equilibrium volumes of six morphological elements (two shoals, two bypassing bars, and two attachment bars), which totals 12 parameters in all. The other equations for calculating actual volume changes in shoals and bars are given as follows (Frey et al. 2012):

$$\frac{dV_e}{dt} = Q_{ie} + Q_{fe} + Q_{ce} - Q_{eb} \tag{14}$$

$$\frac{dV_b}{dt} = Q_{eb} - Q_{ba} \tag{15}$$

$$\frac{dV_a}{dt} = Q_{ba} - Q_{out} \tag{16}$$

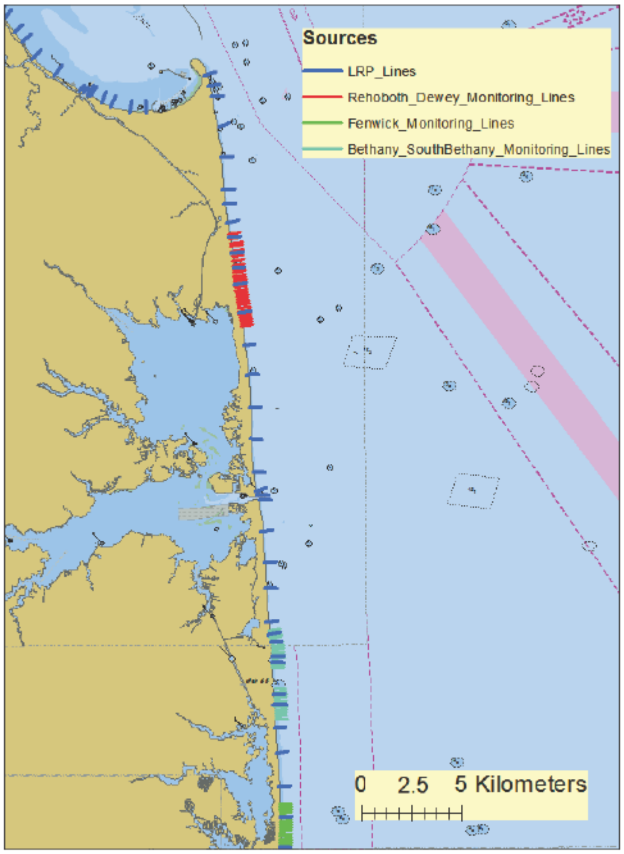
$$\frac{dV_f}{dt} = Q_{cf} - Q_{fe} \tag{17}$$

Based on the above-mentioned Equations (2)–(17) on the sediment bypassing processes, the IRM is able to simulate sediment exchanges between the inlet morphological elements and the evolution of the elements' volumes. However, configuration of the IRM through calibration of all of the 12 empirical parameters for actual and equilibrium volumes is a challenging task and relies on field data of morphological changes near inlet.

3 Shoreline Survey Data for Delaware Coast

Figure 4 shows composite monitoring lines along the Delaware coastlines by the Delaware DNREC and USACE NAP. DNREC monitors shoreline changes. The data set of the Line Reference Points (LRP) (Figure 5) covers the entire length of Delaware coastline over a 10-year period since 2004; however, the coverage is sparse. The beach profiles were surveyed typically out to closure depth, but the exceptional profile near the Indian River entrance was extended to almost 25 m[1] water depth. This data set has highly varying profiles around the zero elevation, making it difficult to determine shorelines by extracting zero elevations.

Figure 4. Compiled shoreline survey data for Delaware coast.



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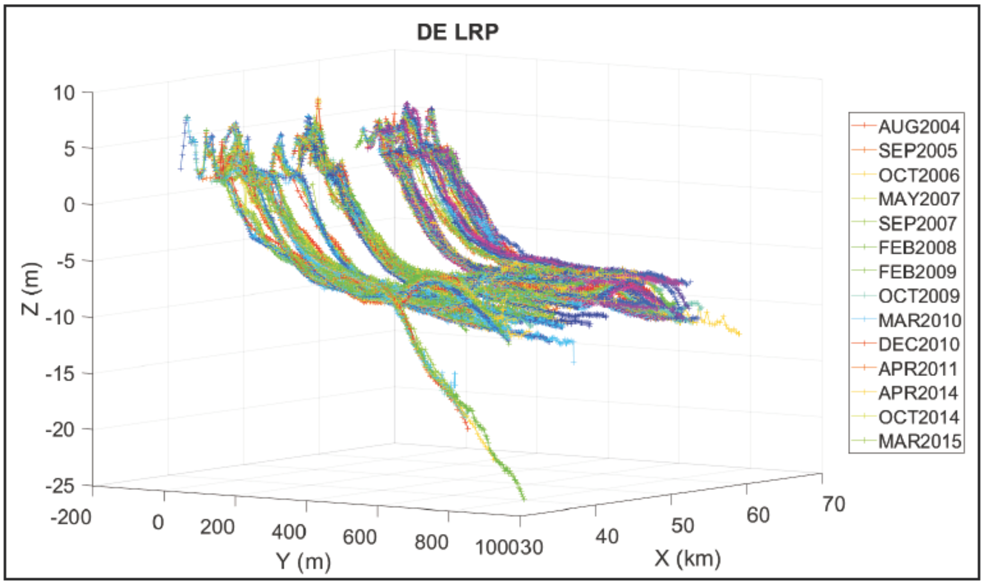
[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Figure 5. Pooled monitoring data from DNREC LRP. One transect located at the Indian River entrance shows the shoreface extending to approximately 25m depth in offshore.



Around the Indian River Inlet, USACE NAP has been monitoring beach profiles since 1985. Profiles along monitoring lines for each survey (Figure 6 and Figure 7) were used to extract shoreline positions defined as zero elevations. In Figure 10, a total of 16 profile survey transects were laid across the coasts at the two sides of the inlet. The shape of the profiles below 10 m depth indicates an ebb shoal offshore. A clear picture of the ebb shoal was captured by the USACE multi-beam hydro survey in 2004 (e.g., Figure 7 in Keshtpoor et al. [2013]). Figure 7 shows time variations of shoreline shape from June 2006 to October 2017. There were 16 times surveys on the north beach and 10 surveys on the south, which were used for validation of the GenCade model. A concave shape of shorelines near the jetties can be seen on the two sides of the beaches. An offset of the shorelines shows the evidence of deficient sediment downdrift to the north. A trend of shoreline accretion was found on the north beach after 2013.

USACE NAP has more spatially and temporally dense survey data focused on three project areas: Rehoboth-Dewey (Figure 8), Bethany-South Bethany (Figure 9), and Fenwick Island (Figure 11). The shorelines were generated for each survey from profile data. Beach fill events are clearly shown as a visible discrepancy between the two consecutive surveys of pre- and post-placements, as shown in Figure 10 for Rehoboth and Figure 11 for Fenwick Island. The shoreline survey data in Fenwick Island were used for the validation of GenCade in this site.

Figure 6. An example of estimating shoreline from survey profiles around the IRI in July 2009. The dash-dotted line is the location of the IRI.

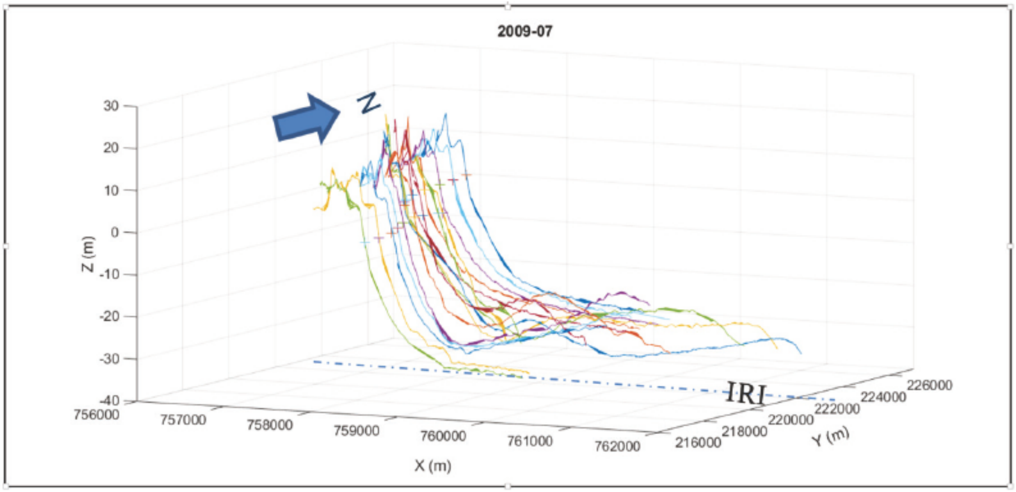


Figure 7. Shoreline profiles over time for coasts around the IRI.

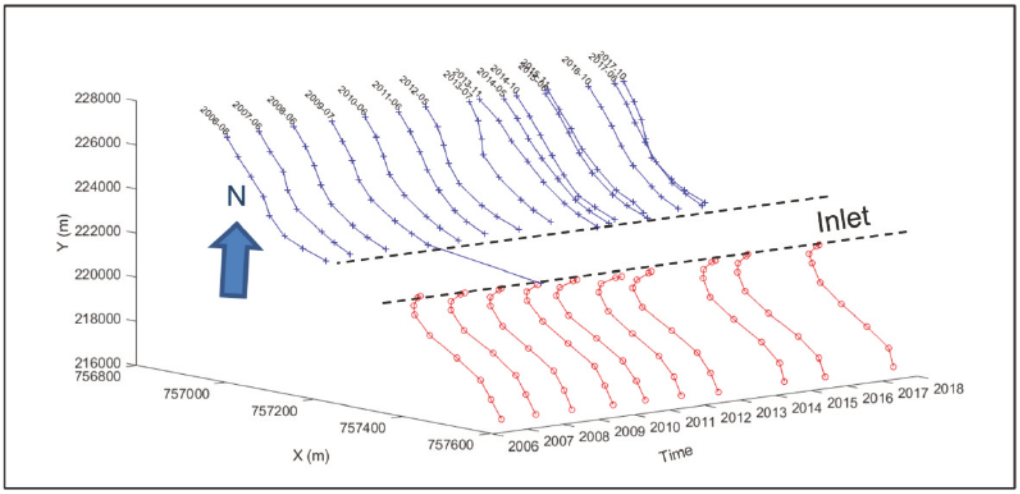


Figure 8. Shorelines from USACE NAP monitoring lines for Rehoboth.

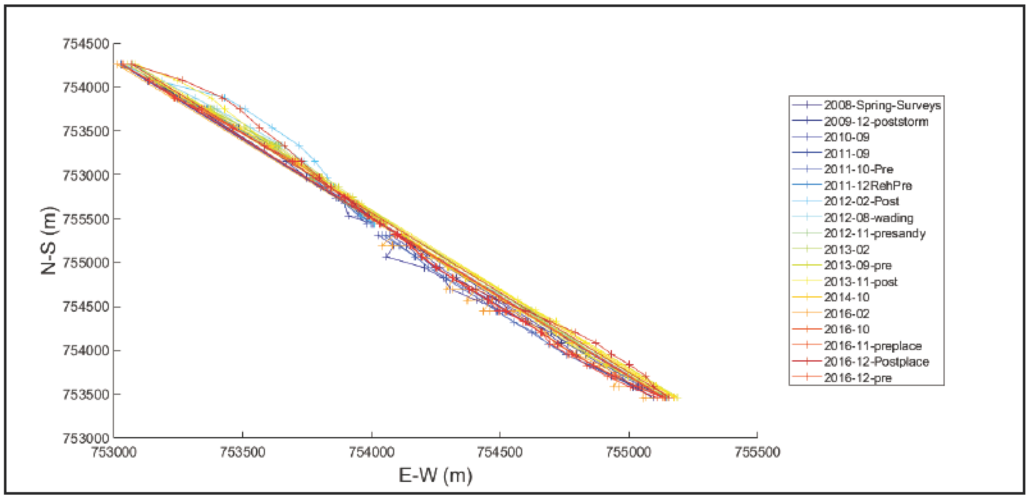


Figure 9. Shorelines from USACE NAP monitoring lines for Bethany-South Bethany.

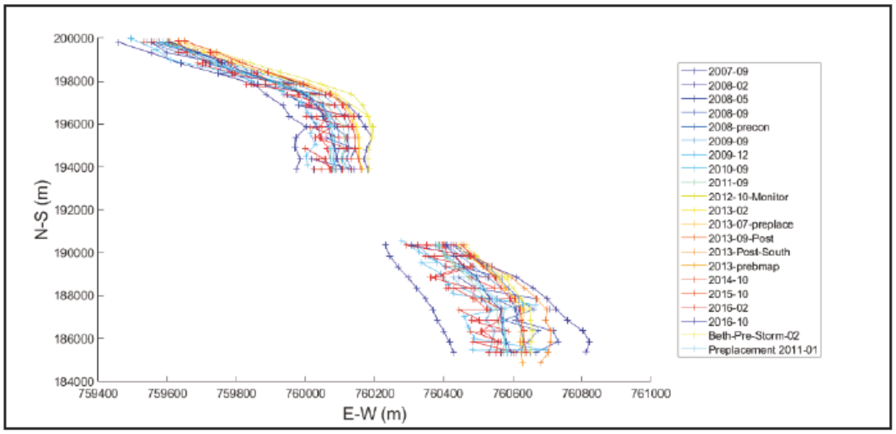


Figure 10. An example to show shorelines reflect beach fill event in Rehoboth.

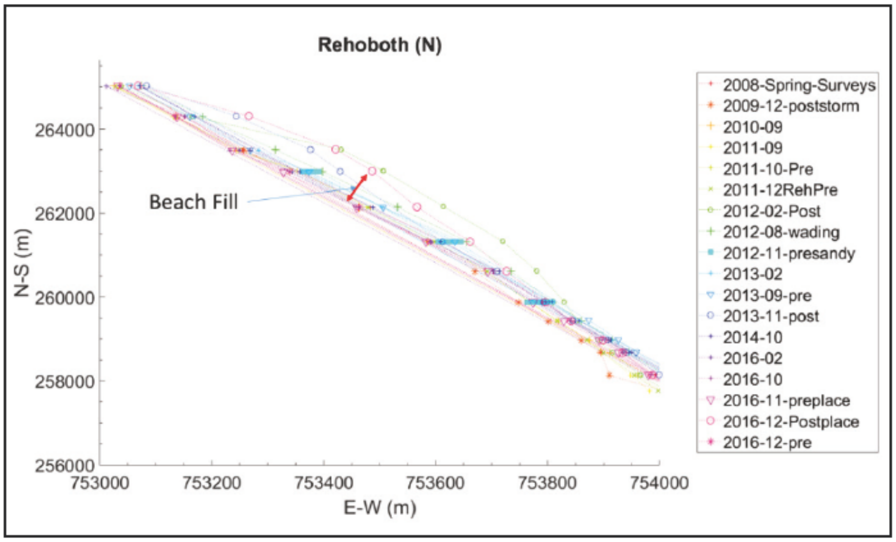
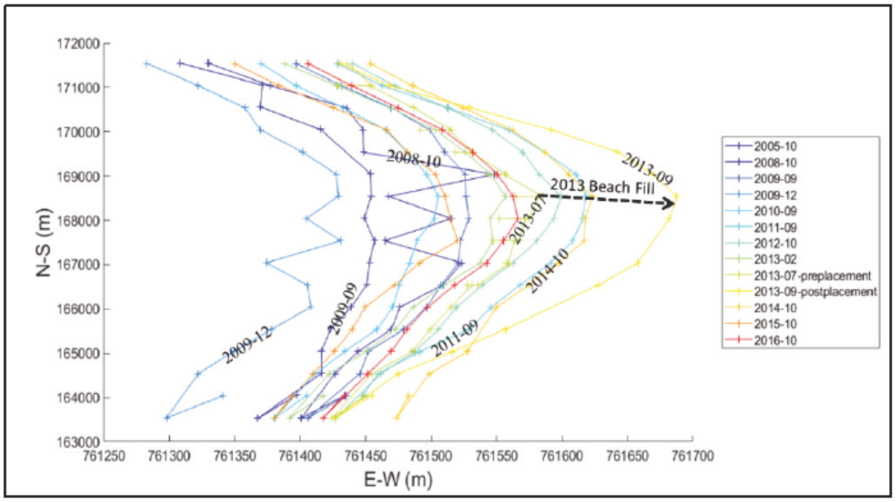


Figure 11. Shorelines from USACE NAP monitoring lines in Fenwick Island. The dashed arrow indicates the shoreline accretion by the 2013 beach fill event.



4 CASE 1: Model Validation on Shoreline Evolution on Coasts near the Indian River Inlet

4.1 GenCade model setup

The GenCade model was configured to simulate shoreline changes on the coasts adjacent to the Indian River Inlet for a 12-year-long period from 03/12/2005 to 12/31/2016. As shown in Figure 12 (a), the simulated coastline is 10,650 m long centered on the inlet, with a grid size of 25 m. The initial shoreline was given by the zero contour in 2005 from the National Coastal Mapping Program.

Based on the profile survey data (shown on Figure 6 and Figure 7), the sediment closure depth and the berm height are estimated to be approximately 10.0 m and 2.0 m, respectively.

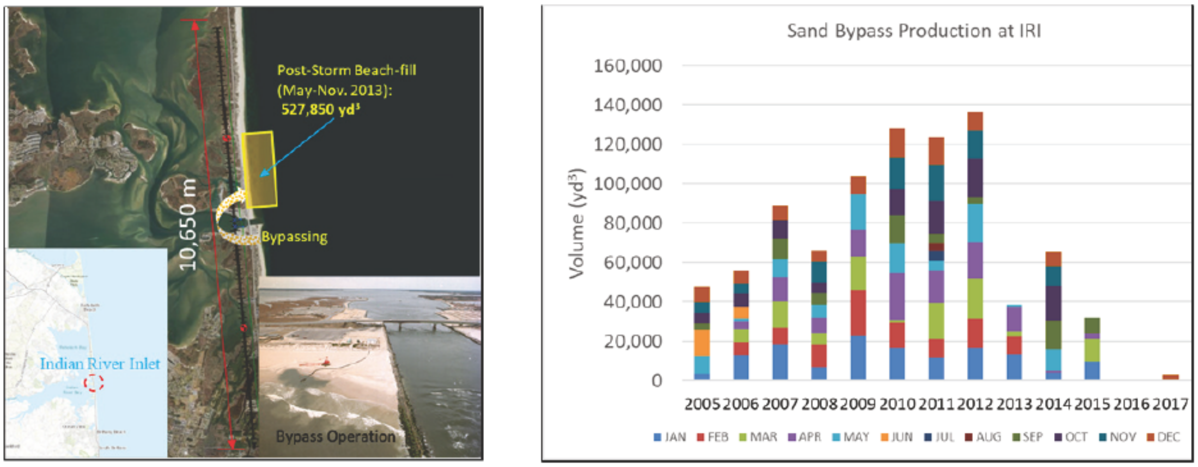
Ramsey (1999) reported that the sediments in the north beach have a medium size in an average, and those in the south are slightly coarser. Roberts et al. (2013) found that the sediment characteristics in the cross-shore profile varies from coarser sandy gravel to well-sorted medium due to storms. For the simplicity of GenCade, the sediment grain size for calculating sediment transport rate was set to 0.3 mm, which is an average value taken from the north and south beaches (Ramsey 1999).

GenCade takes into account the sand bypassing operation in the simulation of shoreline evolution. The history of the sand bypass production volumes during the simulation period (2005–2016) is shown in Figure 12 (b), on which each yearly volume is the sum of all the 12-month bypass production volumes. The maximum annual bypass production is 136,400 yd^3 in 2012, and no sand bypassing was carried out in 2016. Note that there were almost no bypassing operations during the summer season to avoid beachgoers because of the operation rule. This makes a total of 882,155 yd^3 sand bypassed to the north shore during the simulation period. The average annual bypass rate between 2005 and 2015 is 83,824 yd^3, which is slightly more than the prediction values (80,177 yd^3/year), estimated by Keshtpoor et al. (2013), based on historical operation data from 1990 to 2010. This actual average annual bypass rate is, however, less than the designed value (110,000 yd^3/year).

Moreover, a 527,850 yd^3 post-Sandy rehabilitation beach nourishment project took place from May to October 2013 in the north shore[1] and was included in the simulation as well. The nourishment range is approximately 5,000 ft north of the north jetty.

The offshore wave parameters (significant wave height, period, and mean direction) are given by the observation data at two WIS wave buoys, Station ID 63156 (depth=20 m) and 63158 (depth=18 m) (WIS 2019), where the locations are indicated in Figure 1. Over the 12-year simulation period, the average significant wave height is approximately 1.0 m, and the average mean wave direction is from the south-southeast (SSE). This causes a predominant northward longshore sediment transport.

Figure 12. (a) GenCade computational domain along the coast near the IRI shown by a straight line with a ruler (a tick represents a computational transect). The photo at the lower right corner shows the intake of bypassing sand in the south shore. (b) The sand bypass production: the color-coded bars are monthly bypass volume.



(a) GenCade computational domain

(b) Sand bypass production from 2005 to 2017

For the simulation, a fixed boundary condition was chosen where the shorelines at each end of the grid do not move. Due to the lack of observation data of alongshore sediment transport, the empirical parameters K_1 and K_2 in the CERC formula have to be calibrated. In the present study, calibration of the two parameters was carried out by

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[1] Gebert, J. A. Unpublished PowerPoint presentation to ERDC, *Indian River Inlet and DE Coast*. September 24, 2018.

minimizing the root-mean-square errors (RMSE) of shoreline changes through comparing with the observation data. The different values along the north and south shores suggested by Larson et al. (2006) were considered as initial guess values. By means of trial-and-error, it was determined that K_1 was set to 0.17 on the north shore and 0.35 on the south shore. By referring to Frey et al. (2012) for a relationship between K_1 and K_2, $(0.5K_1 < K_2 < 1.5K_1)$, K_2 was estimated to be 0.085 on the north shore and 0.175 on the south, respectively.

For configuring the IRM, it is more difficult to set up the IRM model parameters such as initial and equilibrium volumes of inlet morphological elements. The actual areas of the ebb and flood shoals were described by Keshtpoor et al. (2013) and Gebert (2018). From the hydrographic survey (Figure 7 in Keshtpoor et al. [2013]), a bypass bar and an attachment bar can be seen near the south shore. However, the locations and sizes of the two bars in the north are vague in the survey maps. At the first try of simulation, a set of guess values were estimated based on those limited information and the previous studies (e.g., Larson et al. 2006). Again, a trial-and-error approach was used to determine the best set of the initial and equilibrium values (Table 1), which produced the best results of shoreline positions with the least simulation error.

Table 1. Estimated initial and equilibrium volumes in inlet shoals and bars.

	Initial (yd^3)	Equilibrium (yd^3)
Ebb shoal	4,900,000	7,000,000
Flood shoal	2,800,000	3,500,000
North bypass bar	76,540	175,000
North attachment bar	56,000	70,000
South bypass bar	764,500	1,749,999
South attachment bar	305,800	700,000

In the simulations, cross-shore sediment transport was excluded as there are no observation data for cross-shore transport rate to validate the cross-shore sediment transport model in GenCade developed by Ding et al. (2020). Further investigation on the effect of cross-shore transport will be conducted in the future.

4.2 Model validation results for the coast near the IRI

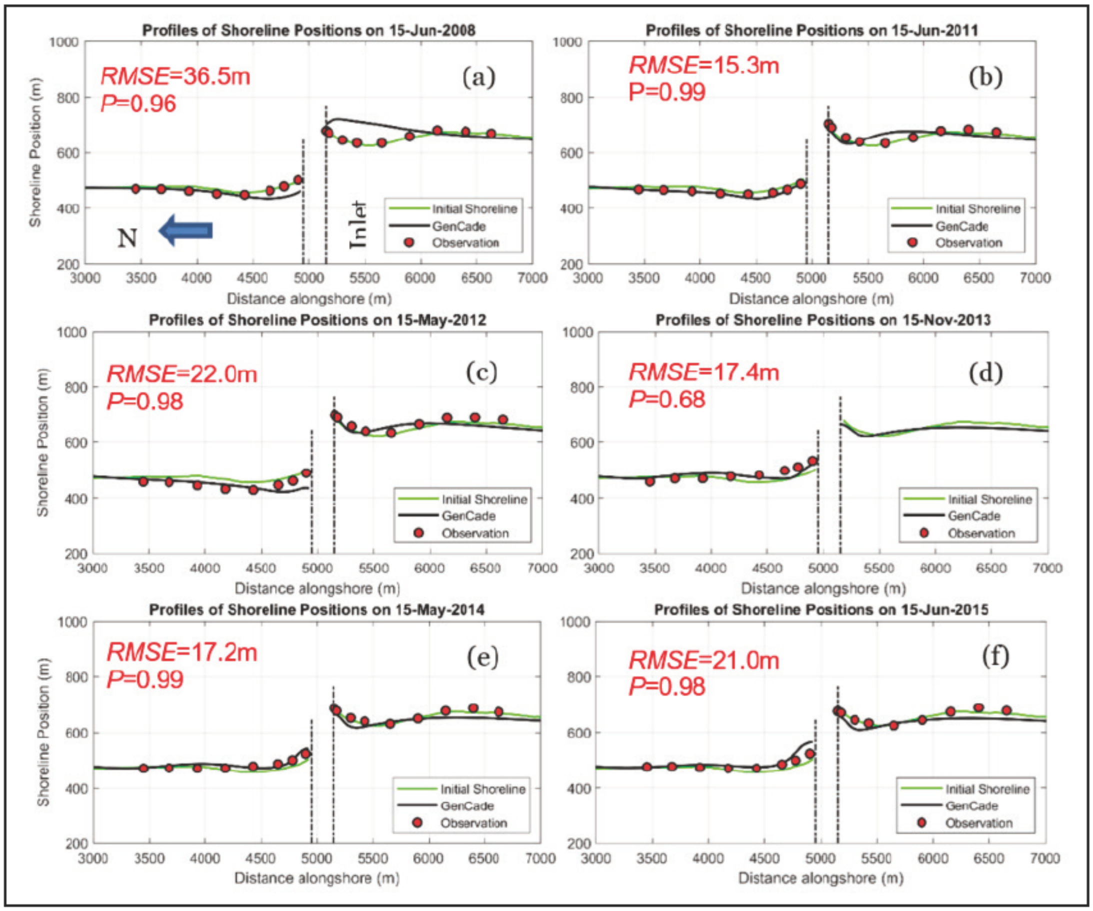
Model validation was conducted by comparing the simulated shoreline positions with the observations, and the statistical errors, the RMSE, and the Pearson correlation coefficient (*P*) are calculated to evaluate the GenCade simulation performance. The definition of the P is

$$P = \frac{\sum_{i=1}^{N}(m_i - \bar{m})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^{N}(m_i - \bar{m})^2 \sum_{i=1}^{N}(O_i - \bar{O})^2}} \tag{18}$$

where m_i= model value, O_i= observation value, N= total number of data, $\bar{m}$= the mean model value, $\bar{O}$ = the mean observation value. The Pearson correlation coefficient has a value between +1 and −1, where 1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation.

As examples, Figure 13 presents the comparisons of shoreline position at six selected times: (a) 15-Jun-2008, (b) 15-Jun-2011, (c) 15-May-2012, (d) 15-Nov-2013, (e) 15-May-2014, and (f) 15-Jun-2015. The observation data were extracted from the beach profiles (Figure 7). The values of RMSE and the *P* for each survey time are written on each figure. In the six survey times, the RMSE varies from 15.3 m on 15-Jun-2011 to 36.5 m on 15-Jun-2008. Except (d), most the *P* values are close to unit, which means the simulated shoreline profiles match with the observed data very well.

Figure 13. Comparisons of shoreline positions between observations and simulations by GenCade. The solid black lines are the simulated shoreline positions. The light green line is the initial shoreline position on 2005/03/12 0:00. The values of RMSE and the Pearson correlation coefficient (P) are given on each plot. The two dash-dotted lines indicate the location of the IRI inlet and the two jetties.

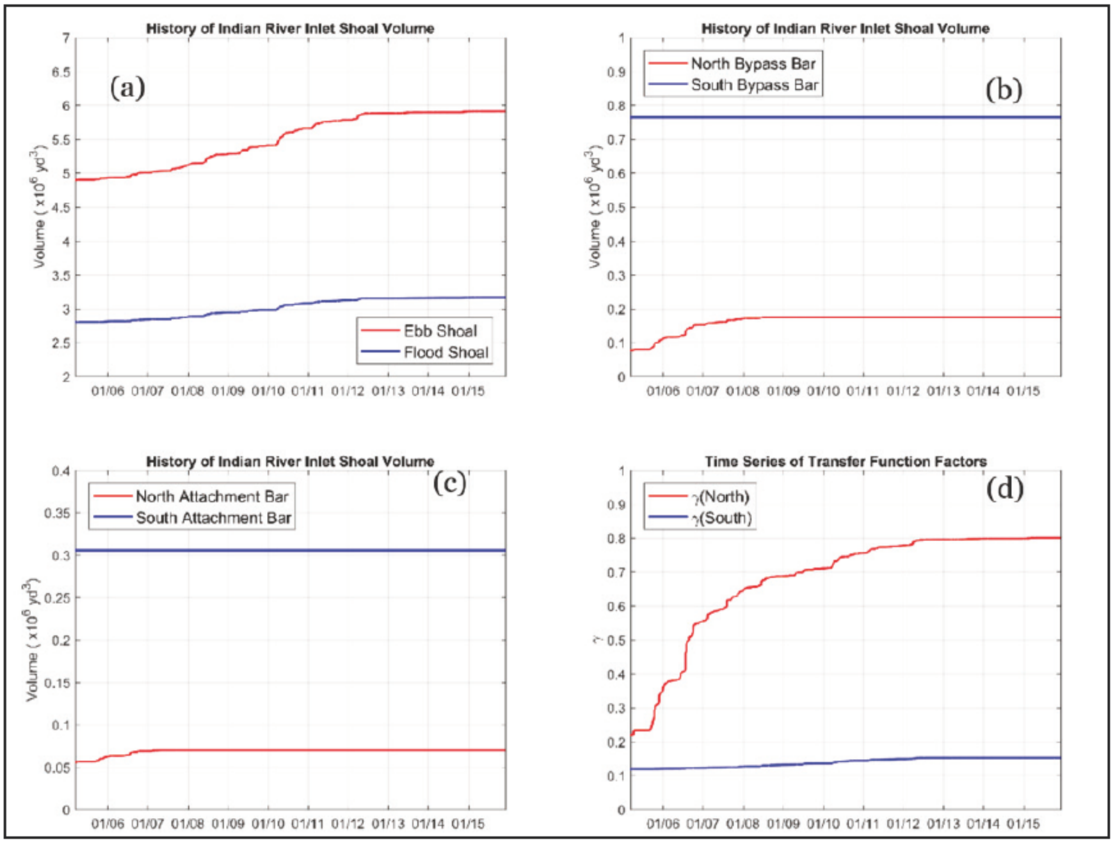


As the GenCade IRM simulates the evolution of volume changes of the inlet shoals and bars (Figure 3), the results can explain how the inlet morphological elements grow and how much the alongshore sediments bypass the inlet. Figure 14 presents the time histories of sand volumes at (a) flood and ebb shoal, (b) bypass bars on the north and south shores, and (3) two attachment bars on the north and south. It shows that the ebb shoal volume changes from its initial volume of 4.9 million yd^3 in 2005 (70% of the equilibrium volume) to 5.9 million yd^3 in 2016 (84% of the equilibrium volume). The flood shoal increases from 2.8 million yd^3 to 3.2 million yd^3 (i.e., from 80% to 91% of the equilibrium volume). The two bars (bypass and attachment) on the north side of the inlet have the volumes increase slightly in the first two years and remain almost constant for the remainder of the simulation. The model shows almost no changes in the two bars in the south.

Figure 14(d) presents the time history of the two inlet sediment transfer factors (γ) calculated by Equation (12), using the sand volumes of the six inlet morphological elements. The north γ, the rate of the sand transferred from the south shore to the north, increases from 0.22 at the beginning to 0.80 after 8 years. That means more than 80% of longshore sediment from the south is transferred to the north during the last 3 years of the simulation. The inlet bypassing rate increased rapidly and possibly exceeds the actual situation. The accelerated bypassing rate may be due to the assumption of the linear relationships for shoal volume changes in Equations (8)–(10). A nonlinear relationship as proposed by Larson et al. (2006) is probably needed in order to improve the IRM performance.

On the other side, the south γ did not change much during the entire simulation period (γ =0.12~0.15), most likely due to the minimal southward longshore sediment transport due to the predominant wave forcing. Except the equilibrium volume of the ebb shoal, the best estimates of the initial and equilibrium volumes of the six inlet morphological elements were obtained through a number of simulations by means of trial-and-error and are presented in Table 1. Further verification of the shoal volume changes by the IRM needs to be completed using hydrographic survey data.

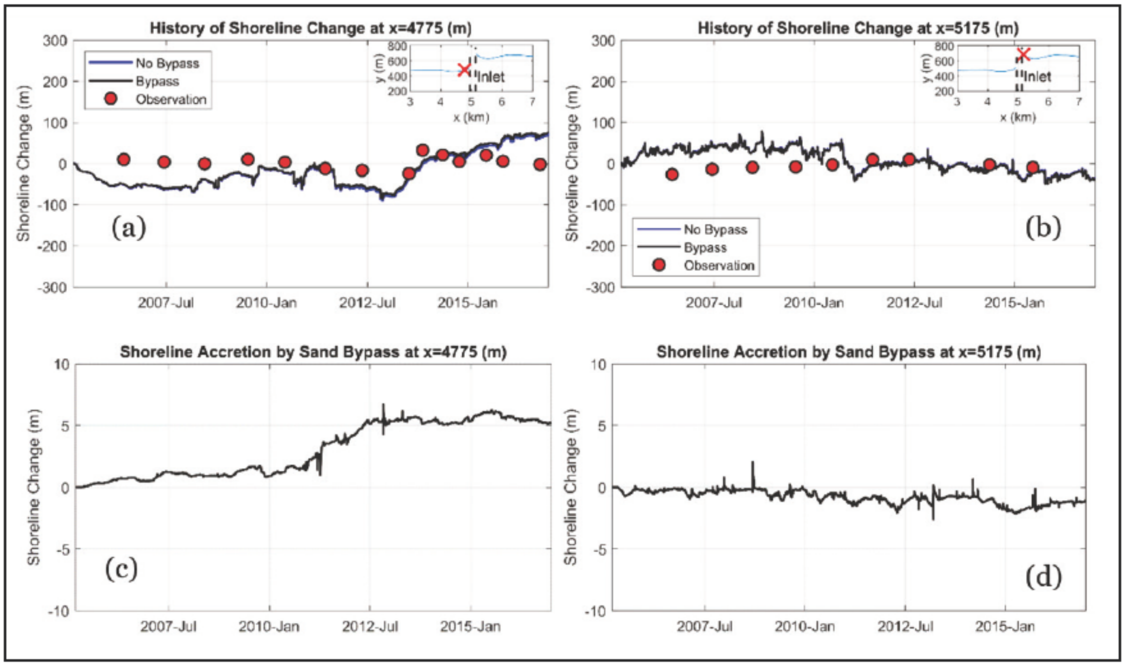
Figure 14. Evolution of inlet shoal and bars. (a) History of the volumes of flood and ebb shoals. (b) Volume changes in the north and south bypass bar. (c) Volume changes in the attachment bars at the north and the south. (d) History of two inlet sediment transfer factors (γ) defined by Equation (12): γ (north) is the transfer factor for the inlet to bypass sand from the south to the north. γ (south) is the one from the north to the south.



To quantify the effect of the sand bypassing operation on shoreline change, a simulation of the shoreline change without sand bypassing has been performed by using this validated GenCade with the same model parameters. As an example, Figure 15 presents comparisons of time histories of shoreline positions with and without the sand bypass at two locations near the jetties at the north (a) and south (b) shores. The two transects located at x=4,775 m and 5,175 m are equivalent to the transect No. 2N and 2S defined in Keshtpoor et al. (2013), respectively. The differences between the two simulated curves with and without sand bypass are hardly seen in the pictures of the shoreline changes. The net changes of the shoreline positions driven solely by the bypass are depicted in Figure 15 (c) and (d) for the two sections, respectively. At the site on the north shore, the bypassing operation drives approximately 1–2 m of shoreline accretion in the first 5 years and then advances up to 5 m at the end of 2016. The shoreline retreat to the south due to sand borrowing was small (Figure 15 d). Note that there are a few spikes in the curves of the net changes, which may be caused by the sudden jumps of the bypass rate, as the model was using the monthly average rate to introduce the sand bypass volume.

Overall, the model correctly responds to the sand bypassing operation on the shoreline changes to the north and the south of the inlet. However, the effect of the shoreline advancement driven by the bypassing may be underestimated due to the assumption of the equilibrium beach profile in GenCade.

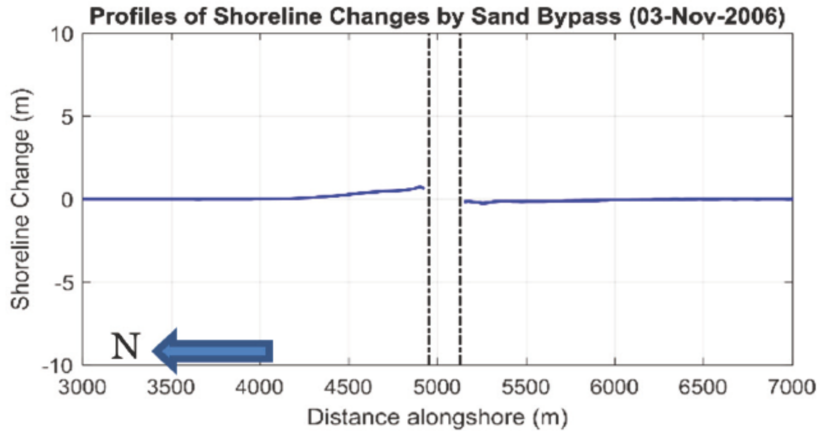
Figure 15. Comparisons of histories of shoreline positions with and without sand bypassing. The observation data are for the results with the sand bypassing. (a) History of shoreline position at the north shore. The symbol "X" in the box at the upper right corner shows the transect of the shoreline position. (b) History of shoreline positions at the south shore. (c) History of shoreline accretion due to sand bypassing at the north shore. (d) The shoreline accretion due to sand bypassing at the south shore.



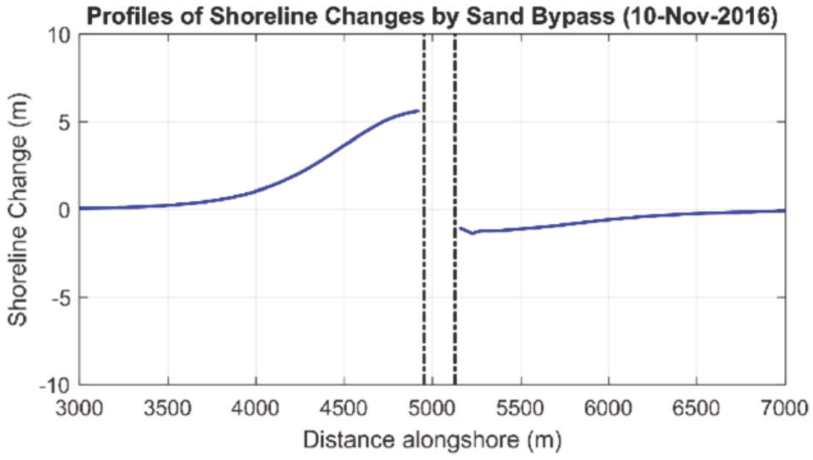
Meanwhile, to find the impact range of the sand bypass operation on both sides of the inlet, the net changes of shorelines at the same time driven only by the sand bypassing were calculated. The profiles of those changes at two selected times are presented in Figure 16. At the end of the second simulation year (03 November 2006) (Figure 16 a) the sand bypassing did not advance much shoreline at the north shore, but it started to accumulate on the beach near the jetty. At the end of the simulation (10

November 2016) (Figure 16b), after 10-year-long operation, a significant amount of net shoreline advance can be seen on the north shore. The advancement effect due to the sand bypassing extends to almost 1,500 m north of the north jetty, which is the same as the conclusion that Keshtpoor et al. (2013) found by analyzing the bypass production and beach profiles observed from 1990 to 2010. On the other side, the net shoreline retreat also appears on the south shore, although the retreat is much less than the magnitude of advancement at the north.

Figure 16. Distributions of net shoreline changes driven by sand bypassing operation on (a) 03 November 2006 and (b) 10 November 2016.



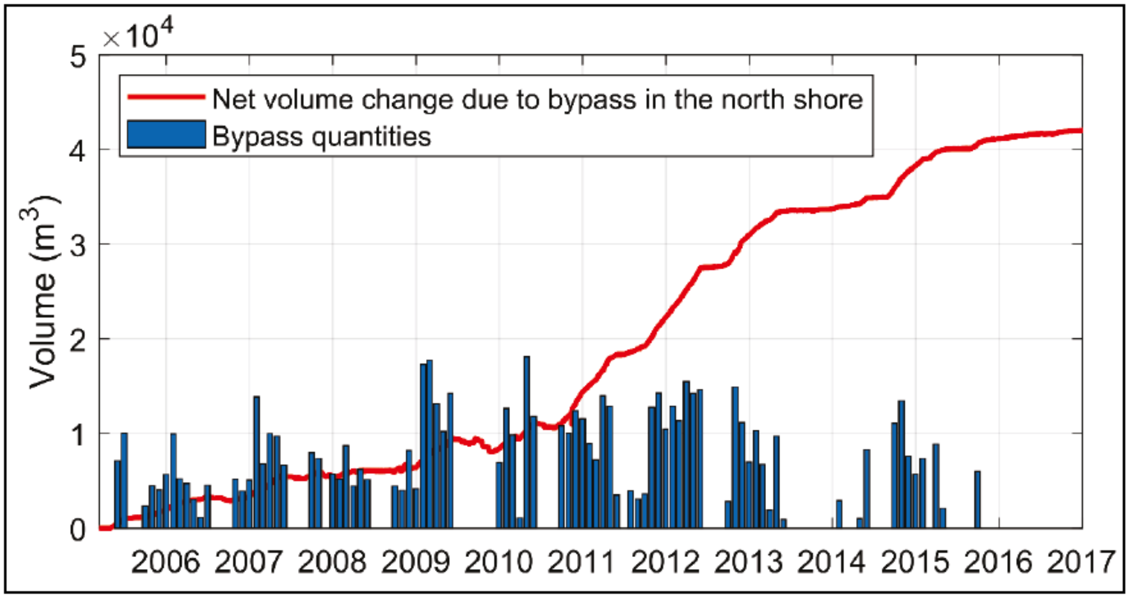
(a) 03-Nov-2006



(b) 10-Nov-2016

Moreover, the net beach accretion volume in the north shore added by the bypass operation can be calculated by multiplying the new changes of beach area with the closure depth (12 m) and berm height (2 m), based on the assumption of equilibrium beach profile. Figure 17 presents the history of this net volume change contributed by the bypass operation, as well as the monthly bypass production. It indicates that approximately 42,050 m^3 of the sand from the bypassing remains in the north shore by the end of 2016. While the simulations provide a rigorous approach to assess the influence of sand bypassing, the uncertainties in the model parameters and variable nature of littoral transport in the area make this conclusion very preliminary.

Figure 17. Net volume of bypass sands in north shore of the IRI. The bars show the monthly bypass production.



5 CASE 2: Model Validation on Shoreline Evolution on Fenwick Island Coast

5.1 GenCade model setup

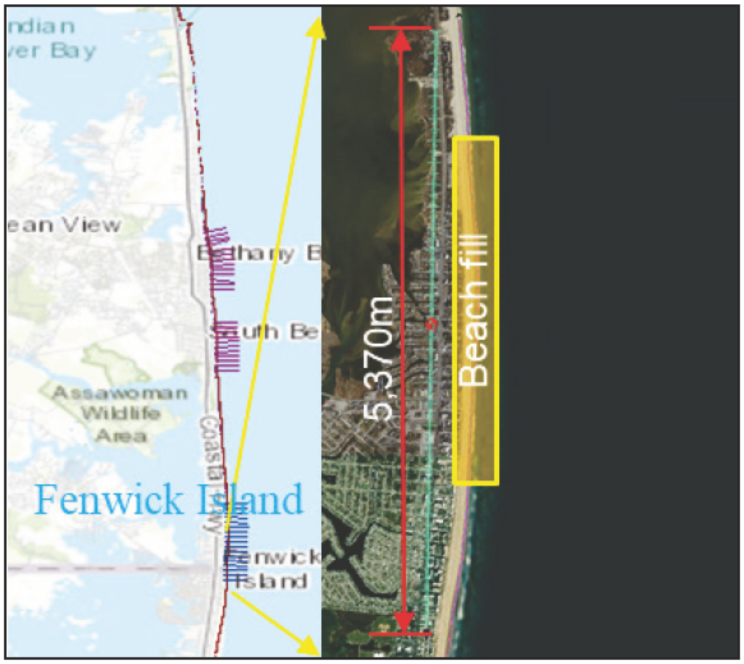
As the long-term trend of shoreline change on the Fenwick Island coast is erosional (e.g., Dolan et al. 1980; Galgano 2008), beach fills have been applied for coastal erosion protection in the area. In order to validate the GenCade model's ability to represent the beach fill process, the GenCade model was developed to cover an 11-year-long period from 10/01/2005 0:00 to 12/31/2016 0:00.

As shown in Figure 18(a), the simulated coastline is approximately 17,550 ft (approximately 5.4 km) long, with a GenCade grid size of 65 ft. During the simulation period, three beach fills were completed over a 6,500 ft wide beach in November 2005 (a total of 864,000 yd^3), August 2011 (332,000 yd^3), and September 2013 (368,000 yd^3) (Gebert 2018). The total volume of beach fill in November 2005 includes 595,400 yd^3 for initial fill and 320,000 yd^3 for a periodic fill. Therefore, an average periodic beach fill volume is approximately 340,000 yd^3. The grain size d_{50} in the site was set to 0.3 mm based on the report of Ramsey (1999). The time step is 3 minutes.

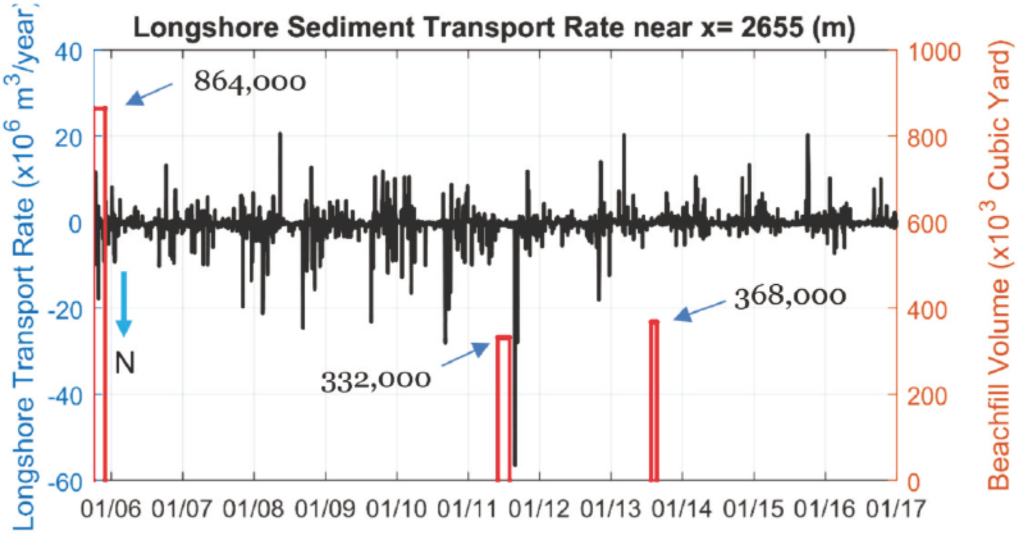
The offshore wave parameters (significant wave height, period, and mean direction) are given by observation data at the WIS wave buoy, Station ID 63160 (depth=14 m, Figure 1) (WIS 2019). Over the 11-year simulation period, the average significant wave height is 1.07 m, and the average mean wave direction is -12.92 degrees relative to the shore normal, from SSE. The predominant longshore sediment movement is toward the north, similar to that near the Indian River Inlet.

After a number of trial-and-error tests, it was found that the best empirical parameters K_1 and K_2 in GenCade are 0.40 and 0.25, respectively. For this simulation, calculation of cross-shore sediment transport is also excluded.

Figure 18. (a) GenCade model range on the Fenwick Island coast and beach fill areas. The x-axis of the model is toward the south. (b) The solid black line is the time series of longshore transport rate calculated at the middle of the study coastline (x=2655 m). A negative transport rate is toward the north. The red bars show the beach fill volumes in the three events in November 2005, August 2011, and September 2013.



(b) GenCade computational domain.



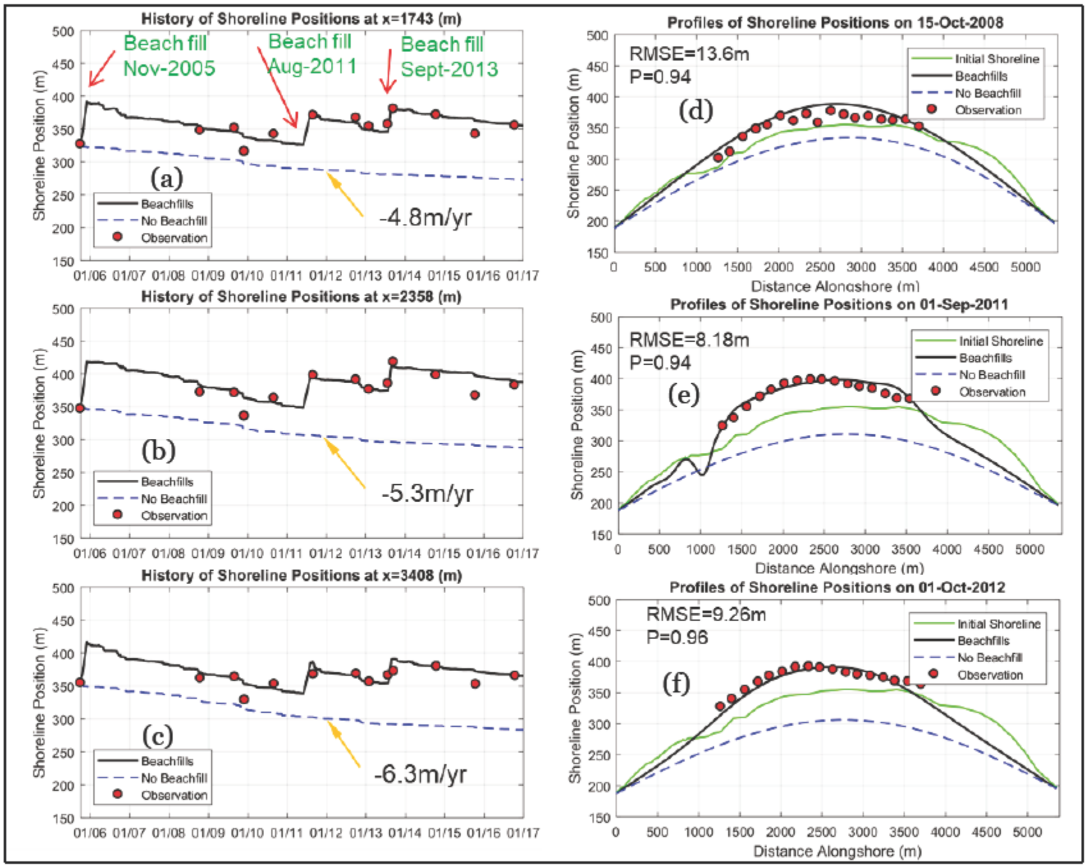
(b) Longshore transport rate (a solid black line) at x=2655 m and actual beachfill volumes (three red bars).

5.2 Simulation results of shoreline change on Fenwick Island Coast

Similar to the previous case, the model skill was assessed by comparing the simulated shoreline positions with the observations. Comparisons of shoreline positions between simulation and observation are shown in Figure 19, (a)–(c) histories of shoreline positions at three locations (x=1,743, 2,358, and 3,408 m), and (d)–(f) profiles of shoreline positions at three survey times: 10/15/2008, 09/01/2011, and 10/01/2012. The statistical errors were calculated based on the profile survey data, which are presented on Figure 19 (d)–(f). The ranges of RMSE and the Pearson correlation coefficient indicate that the simulated shoreline changes over the 11-year period are in excellent agreement with the survey data.

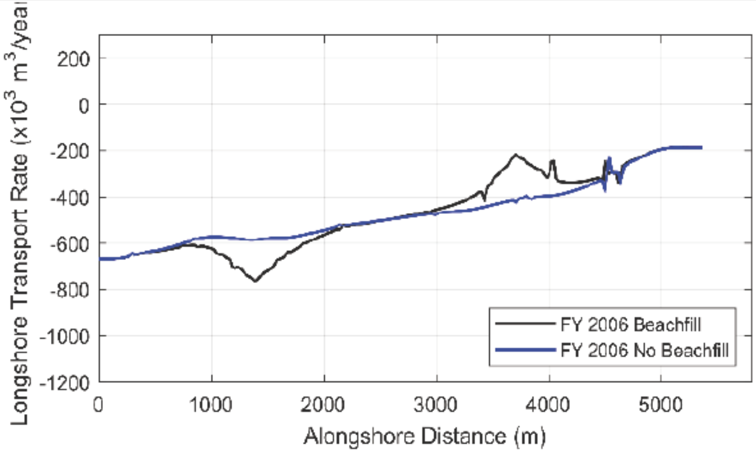
To assess the performance of the beach fill, the simulation results without the three beach fill events (the dashed blue lines) are also added on the figures. It is found that without the beach fills, the average annual shoreline retreat rates at the three locations are 4.8, 5.3, and 6.3 m. If no beach fills were placed, the shoreline retreat after 11 years at the end of 2016 could be more than 60 m at the farthest-south location.

Figure 19. Comparison of time history of shoreline positions and profiles: (a)–(c) Histories of shoreline positions at three locations (x=1,743, 2,358, and 3,408 m). (d)–(f) Profiles of shoreline positions on three survey times, 10/15/2008, 09/01/2011, and /10/01/2012.

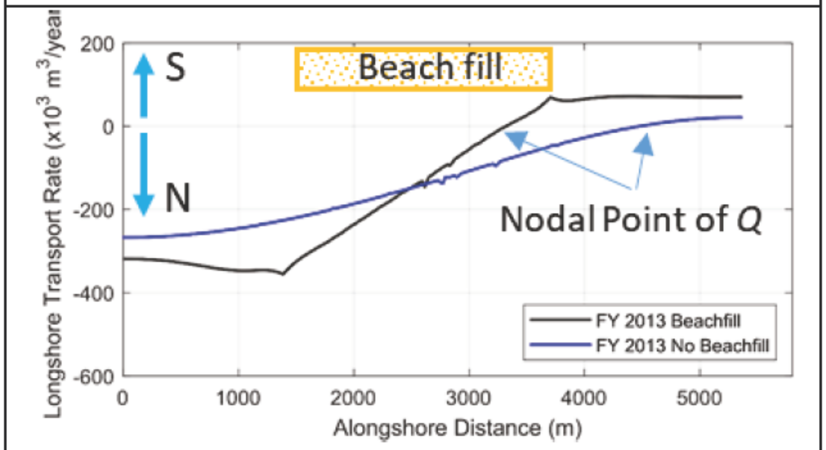


Longshore sediment movement and beach fills (Figure 18b) are two major reasons that drive shoreline changes on the Delaware coast. The gradient of longshore transport determines whether the shoreline retreats or advances. Figure 20 presents the average annual longshore transport rates with and without the beach fills in Fiscal Year (FY) 2006 (a) and FY2013 (b). The positive values of the rate indicate southward sediment transport. As shown, Figure 20 (a), the first beach fill in November 2005 altered the transport gradient, which caused shoreline changes (erosion and accretion) at the ends of the beach fill range. In FY2013 (Figure 20b), the three beach fills induced greater gradient of the average longshore transport than that without beach fills. It means that the shoreline erosion becomes faster than that without beach fills. A nodal point (indicated by the blue arrow) at which the longshore transport starts to turn its direction can be found along the southern part of the beach. The nodal point of the average longshore transport moved approximately 1,000 m to the north, in comparison to that without beach fills. While the location of a nodal point is a good indicator of shoreline erosion, predictions of spatio-temporal changes of shoreline positions driven by physical processes and erosion protection practices are still dependent on a shoreline evolution model such as GenCade.

Figure 20. Average annual longshore sediment transport and nodal points: The positive transport rate is toward the south. The solid black lines are for the case with the beach fills. The blue lines are for that without any beach fills.



(a) For FY2006



(b) For FY2013

6 Conclusions and Recommendations

6.1 Conclusions

This technical report presents two applications of the GenCade model to simulate shoreline changes along the Delaware Coast driven by offshore waves and coastal protection practices such as beach fill, sand bypassing, and sand nourishment. Two site-specific shoreline evolution models were developed: one is for the coasts adjacent to the Indian River Inlet and another is for the shoreline of Fenwick Island. The two models were successfully validated through evaluating statistical errors between simulations and observations such as the RMSE and the Pearson correlation coefficient (P). The observed shoreline positions were obtained by extracting the positions at the vertical datum (North American Vertical Datum of 1988) from the survey data of beach profiles, which were measured by DNREC and USACE NAP.

For validation of GenCade with the Inlet Reservoir Model (IRM), which has multiple parameters of shoal volumes to be determined, an inlet sediment transfer factor (γ) is defined to quantify the rate of longshore sediments transferred across inlet from the updrift side to the downdrift. This transfer factor explains the capability of sediment bypassing through an inlet. It also makes calibration of multiple parameters in this complicated IRM model relatively easier.

Simulation of shoreline changes was achieved for the coasts near the Indian River Inlet over a nearly 12-year-long period from 2005 to 2016. The actual monthly sand bypassing volumes and the post-Sandy beach nourishment were included in the simulation. The best results of shoreline changes were obtained by calibrating three model empirical parameters, K_1, and K_2, and the inlet sediment transfer factor (γ). The model skill was assessed by the values of RMSE and P of the simulated shoreline positions. The results of IRM provide details on evolution of inlet morphology elements volumes such as flood/ebb shoals and attachment/bypass bars. Variation of the inlet sediment transfer factor connects with the dynamic process of sediment passing across the inlet. By comparing the simulated shoreline positions with and without the sand bypassing operation, the net volumes of sand accretion in the north shore due to the bypassing operation were calculated, which explain the bypassing operation efficiency.

The second case is to reproduce the shoreline evolution on Fenwick Island, which suffers from chronic erosion due to wave-induced longshore transport. An 11-year-long shoreline evolution from 2005 to 2016 was simulated by including three periodic beach fills, of which the volumes and schedules are based on actual project processes. Through calibration of the model parameters (K_1 and K_2), the validated GenCade model produced shoreline changes in good agreement with the observations. In addition, the effect of beach fills was quantified by comparisons of shoreline positions between simulations with and without beach fills. It confirms that the beach fill plays an important role in maintaining the shoreline positions in Fenwick Island.

6.2 Recommendations

For future studies, the inlet sediment transfer factor (γ) for the IRI has to be validated by using the measured volume changes of inlet morphology elements (i.e., shoals and bars) and longshore sediment transport rates at both sides of the Inlet. Since the cross-shore sediment transport is another factor to reshape beach profile during and after beach fill events, the cross-shore sediment transport model (Ding et al. 2020) should be included in the simulations of shoreline changes.

In the present two study sites, the assumption of the fixed shoreline positions at two ends are given as the boundary conditions for the simulations. As the beach fills have been carried out in other places such as Rehoboth Beach, Dewey Beach, and Bethany Beach/South Bethany, it is necessary to develop a regional-scale shoreline evolution model to cover all the sites with the beach fills/nourishments. To do so, the uncertainties due to the assumption of the fixed boundary conditions can be minimized, and the interactive influence of coastal protection practices at different sites can be evaluated.

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Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	0.0254	meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
yards	0.9144	meters

Acronyms and Abbreviations

CERC	Coastal Engineering Research Center
DNREC	Department of Natural Resources and Environmental Control
IRI	Indian River Inlet
IRM	Inlet Reservoir Model
LRP	Line Reference Points
NAP	Philadelphia District
SMS	Surface-water Modeling System
USACE	US Army Corps of Engineers
WIS	Wave Information Studies
SSE	south-southeast
RMSE	root-mean-square error
FY	Fiscal Year

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14. ABSTRACT
This technical report presents two applications of the GenCade model to simulate long-term shoreline evolution along the Delaware Coast driven by waves, inlet sediment transport, and longshore sediment transport. The simulations also include coastal protection practices such as periodic beach fills, post-storm nourishment, and sand bypassing. Two site-specific GenCade models were developed: one is for the coasts adjacent to the Indian River Inlet (IRI) and another is for Fenwick Island. In the first model, the sediment exchanges among the shoals and bars of the inlet were simulated by the Inlet Reservoir Model (IRM) in the GenCade. An inlet sediment transfer factor (γ) was derived from the IRM to quantify the capability of inlet sediment bypassing, measured by a rate of longshore sediments transferred across an inlet from the updrift side to the downdrift side. The second model for the Fenwick Island coast was validated by simulating an 11-year-long shoreline evolution driven by longshore sediment transport and periodic beach fills. Validation of the two models was achieved through evaluating statistical errors of simulations. The effects of the sand bypassing operation across the IRI and the beach fills in Fenwick Island were examined by comparing simulation results with and without those protection practices. Results of the study will benefit planning and management of coastal sediments at the sites.

15. SUBJECT TERMS
Beaches, Beach nourishment, Coast changes—Computer simulation, Delaware, Ocean waves, Sediment transport, Shorelines

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