

greatest negative (landward) shoreline change rate, when annualized between April 2021 and May 2023 (-27.6 ft./yr.).

### **South Monitoring Area (D-19 to D-34)**

Since monitoring of the Duck shoreline began in September 2013 to May 2023, the average position of the +6.0 ft. NAVD88 contour along the South Monitoring Area (D-19 to D-34) moved landward -8.9 ft. (Table 3). This is equivalent to a rate of -1.1 ft./yr. when annualized. As shown in Figure 4, between September 2013 and December 2017, the South Monitoring Area experienced negative shoreline change. Between December 2017 and May 2019, the area experienced an average positive shoreline change. However, between May 2019 and May 2023, the average shoreline change has been negative.

While Figure 4 reflects the average shoreline change, there is considerable amount of variability in shoreline change trends from profile to profile as seen in Table 3 and Table 4. Between September 2013 and May 2023, the greatest negative change in the position of the +6.0 ft. NAVD88 contour was observed at station D-30 (approximately 100 ft. north of LaLa Ct. beach access) which experienced shoreline recession at a rate of -4.8 ft./yr. Over the same time, the greatest positive shoreline change was observed at station D-20 (approximately 1,000 ft. north of the FRF pier), which experienced shoreline advance at +2.5 ft./yr. over the 9.7-year period.

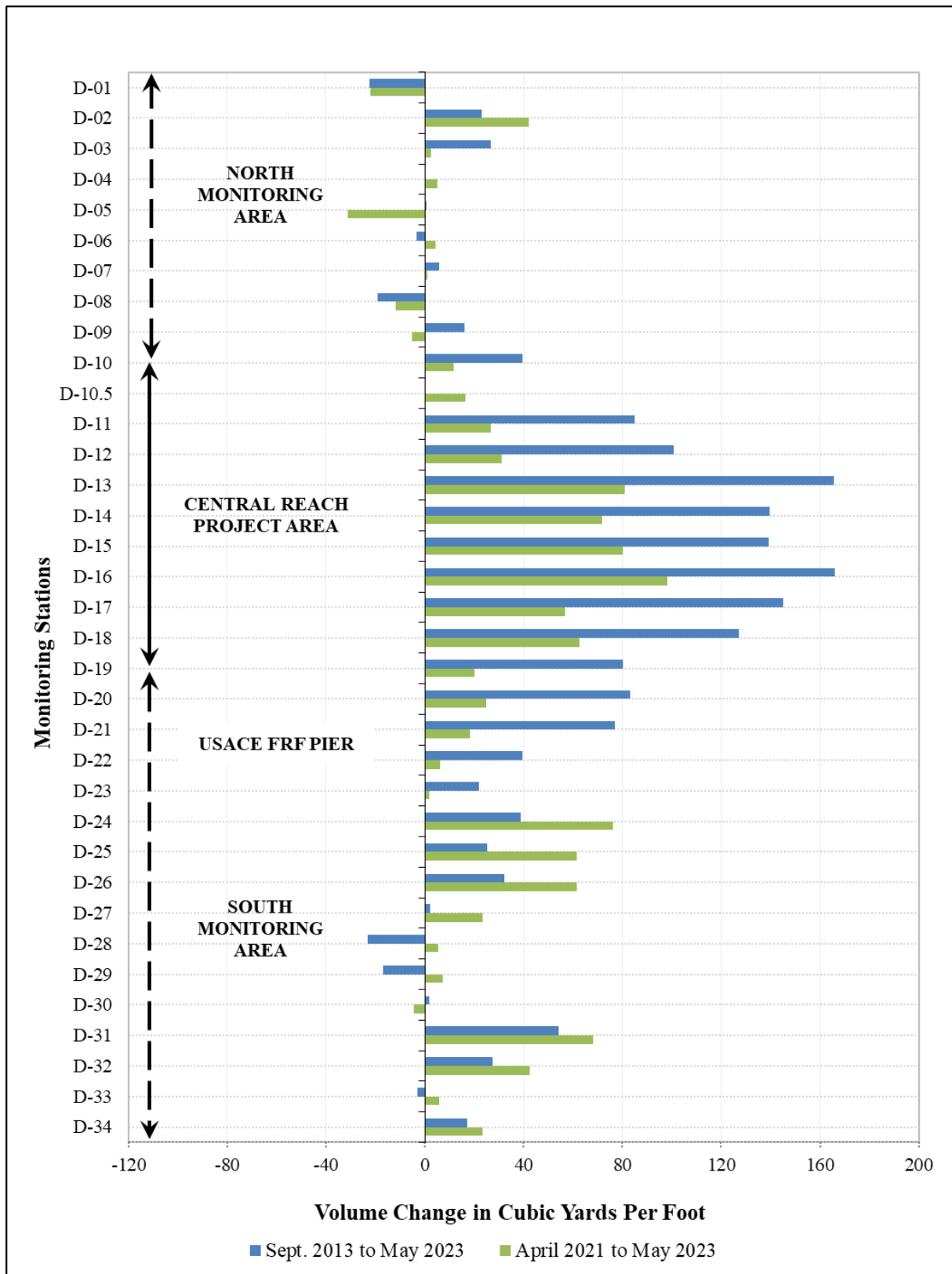
During the recent survey interval from April 2021 to May 2023 the average shoreline change in the South Monitoring Area was +6.2 ft. Between April 2021 and May 2023, the greatest negative change in the position of the +6.0 ft. NAVD88 contour was observed at station D-19 (northern boundary of FRF property) of 34.1 ft. (landward movement) over the 2.1-year period. Over the same time, the greatest positive shoreline change was observed at station D-23 (800 ft. south of FRF pier), which experienced 45.4 ft. of change in the 6.0 ft. NAVD88 contour. The average shoreline change measured within the FRF property between station D-19 (northern boundary of FRF property) and D-22 (650 ft. south of FRF pier) was -8.2 ft. (landward movement) between April 2021 and May 2023. Between stations D-23 (800 ft. south of FRF pier) and D-34 (13<sup>th</sup> Ave), the average shoreline change was +9.6 ft. between April 2021 and May 2023.

## **V. VOLUMETRIC CHANGE RESULTS**

Volumetric changes measured over the entire monitoring area for various time periods are provided in Table 5. The volume changes are given in terms of cubic yards/foot of shoreline/year (cy/ft./yr.). Volume change rates were evaluated for the periods from September 2013 to May 2023, December 2017 to January 2023, and April 2021 to May 2023. The December 2017 to January 2023 surveys show changes occurring between the 2017 and 2023 beach nourishment projects and provide the most comprehensive indication of the 2017 project's performance. The September 2013 to May 2023 and April 2021 to May 2023 surveys present the long-term and recent volume changes. These changes are mainly focused on evaluating the changes outside of the Central Reach Project Area since the volumes in the Central Reach Project Area are heavily influenced by the construction of the 2017 and 2023 projects. Future annual monitoring reports will reference volume changes in the Central Reach Project Area relative to the May 2023 condition to track the performance of the 2023 project. This report also includes a volume change relative to the September 2013 survey, which is referred to as the baseline survey, which represents the initial survey conducted by CPE during the planning process for the project. Table 5 provides the volume change rates at each monitoring station along the Town of Duck for each of the monitoring periods. Figure 5 graphically depicts the volumetric changes calculated above -24 ft. NAVD88 between September 2013 and May 2023 as well as changes measured from April 2021 and May 2023.

**Table 5. Volumetric Change Rates (cy/ft./yr.) along Duck above -24 ft. NAVD88**

PROFILE		Sept. 2013 (Baseline) to May 2023 (2023 Post-Con)	Dec. 2017 (2017 Post- Con) to Jan. 2023 (2023 Pre-Con)	April 2021 to May 2023 (2023 Post-Con)
North Monitoring Area	D-01	-2.3		-10.6
	D-02	2.4		20.2
	D-03	2.8		1.2
	D-04	0.0		2.4
	D-05	0.1		-14.9
	D-06	-0.4		2.1
	D-07	0.6		0.5
	D-08	-2.0		-5.7
	D-09	1.7		-2.4
Central Reach Project Area	D-10	4.1	0.8	5.6
	D-10.5	-	-	8.0
	D-11	8.8	-12.3	12.8
	D-12	10.4	-15.1	15.0
	D-13	17.1	-4.9	38.9
	D-14	14.4	-28.2	34.5
	D-15	14.4	-19.1	38.5
	D-16	17.2	-13.7	47.1
	D-17	15.0	-6.5	27.3
	D-18	13.2	-9.0	30.1
	D-19	8.3	-0.1	9.6
South Monitoring Area	D-20	8.6		11.9
	D-21	7.9		8.8
	D-22	4.1		2.9
	D-23	2.3		0.9
	D-24	4.0		36.5
	D-25	2.6		29.5
	D-26	3.3		29.5
	D-27	0.2		11.3
	D-28	-2.4		2.6
	D-29	-1.8		3.5
	D-30	0.2		-2.2
	D-31	5.6		32.7
	D-32	2.8		20.4
	D-33	-0.3		2.9
	D-34	1.8		11.3
NORTH MONITORING AREA (D-01 TO D-10)		0.7		-0.1
CENTRAL REACH PROJECT AREA (D-10 TO D-19)		12.3	-10.8	24.3
SOUTH MONITORING AREA (D-19 TO D-34)		3.0		13.3



**Figure 5. Volume Changes (cubic yards/foot) measured between Sept. 2013 to May 2023 and April 2021 to May 2023.**

### **2017 Beach Fill Volumes**

Between May and June 2017, a total of 1.26 million cubic yards of fill were placed along the Duck shoreline between stations D-10 and D-19 (Central Reach Project) (APTIM, 2020). The performance of the 2017 Central Reach Project is based on changes that occurred relative to the conditional monitoring survey conducted in December 2017. Based on volume changes computed between April 2017 and December 2017, a volume change of approximately 963,100 cubic yards were measured on the active profile (above the -24-foot NAVD88 contour) from station D-10 to station D-19 (APTIM, 2020). For more information on why this method of assessing volume was used, please refer to the 2018 Shoreline and Volume Change Monitoring Report (APTIM, 2018).

### **2023 Beach Fill Volumes**

Between April and May 2023, the 2023 beach renourishment project placed a total of 576,800 cubic yards of fill along the Duck shoreline between stations D-10 and D-19 (Central Reach Project). The May 2023 survey has been adopted to represent the post-construction conditions within the Central Reach Project Area. Future annual monitoring reports will reference shoreline and volume changes in the Central Reach Project Area relative to the May 2023 condition to track the performance of the 2023 project.

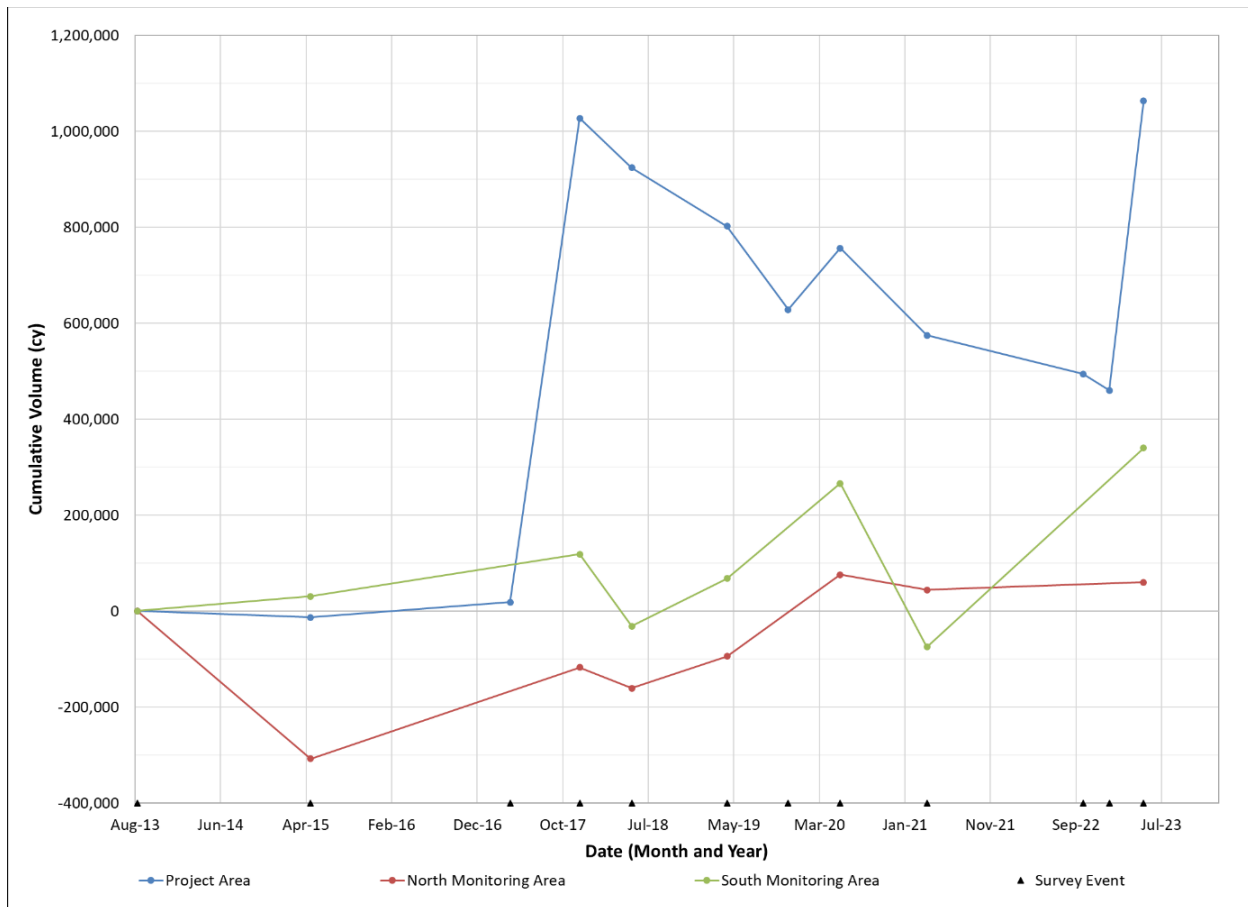
### **Central Reach Project Area (D-10 to D-19)**

From September 2013 to May 2023 the Central Reach Project Area experienced a net positive volumetric change of approximately 1,061,000 cy, which equates to an annual average density change rate of +12.3 cy/ft./yr. This positive trend is reflective of both the 2017 and 2023 beach nourishment projects.

With regards to the performance of the beach fill placed along the Central Reach Project in 2017, beach profile monitoring surveys indicate a volume change of approximately -521,800 cubic yards between December 2017 and January 2023. This equates to a rate of -10.8 cy/ft./yr. when annualized. **As of January 2023, the analysis indicated that the Town of Duck beach nourishment project had approximately 46% of the initial fill volume remaining as measured in December 2017 above the -24-foot NAVD88 contour.**

Figure 6 shows the cumulative volumetric changes for the Town of Duck measured since the baseline survey was conducted in September 2013. Cumulative volumetric changes are displayed for the Central Reach Project Area, North Monitoring Area, and South Monitoring Area. The large increase in the Central Reach Project Area (blue line) between April 2017 and December 2017 reflects the volume gain associated with the 2017 project construction. A relatively linear trend in erosion was measured from December 2017 to January 2023. The large increase in the Central Reach Project Area (blue line) between January 2023 and May 2023 is reflective of the volume added associated with the construction of the 2023 project.

The net volumetric change measured from April 2021 to May 2023, was a positive volumetric change of approximately 496,900 cubic yards. This is equivalent to an average annual rate of approximately +24.3 cy/ft./yr. The majority of that positive volumetric change is associated with the construction of the 2023 Project that placed approximately 576,800 cy within the Central Reach Project Area. Figure 6 illustrates the erosional trend that occurred along the Central Reach Project Area between April 2021 and Jan. 2023. During this time, a negative volumetric change of approximately 108,000 cy was measured, which is equivalent to an average change rate of -7.3 cy/ft./yr. this approximately 21-month period was followed by a significant positive volumetric change between January and May 2023, associated with the 2023 beach nourishment project.




**Figure 6. Average Cumulative Volumetric Changes above the -24 ft. NAVD88 contour since September 2013 in the Central Reach Project Area and the North and South Monitoring Areas**

#### **North Monitoring Area (D-01 to D-10)**

From September 2013 to May 2023 the North Monitoring Area experienced a net positive volumetric change of approximately 60,100 cy. This equates to an annual average density change rate of +0.7 cy/ft./yr. and is reflective of relative stability within the area over the 9.7-year period. As shown in Table 5, the rates of change varied from profile to profile within the North Monitoring Area ranging from positive rate of 2.8 cy/ft./yr. at station D-03 (south end of S. Baum Trail) to a negative rate of -2.3 at station D-01 (approximately 300 feet south of northern Town boundary).

In Figure 6, the cumulative volumetric changes in the North Monitoring Area (red line) indicates a relatively steep erosional trend between September 2013 and May 2015, prior to the 2017 Central Reach Project. This erosional trend resulted in a negative volumetric change of approximately 308,000 cy. A positive volumetric trend was measured between May 2015 and December 2017. Between December 2017 and June 2020, positive volumetric change occurred in the North Monitoring Area. It is noteworthy to report that although approximately 308,000 cy of negative volumetric change was measured between September 2013 and May 2015, the volumetric changes that occurred between May 2015 and June 2020 more than offset those previous losses and resulted in a cumulative positive volumetric change of approximately 76,000 cy, relative to the September 2013 condition. Between June 2020 and May 2023, the North Monitoring Area has remained relatively stable with regards to volumetric changes.



Between June 2020 and April 2021, the volumetric change rate along the North Monitoring Area between station D-01 (Station 1 Ln.) and station D-10 (Skimmer Way) was -2.9 cy/ft./yr. (CPE, 2021). The more recent volumetric change rate measured between April 2021 and May 2023 shows that the North Monitoring Area remained stable on average with a modest change of -0.1 cy/ft./yr.

#### **South Monitoring Area (D-19 to D-34)**

From September 2013 to May 2023 the South Monitoring Area experienced a net positive volumetric change of approximately 339,900 cy. This equates to an annual average density change rate of +3.0 cy/ft./yr. over the 9.7-year period since September 2013. As shown in Table 5, the rates of change varied from profile to profile within the South Monitoring Area ranging from a positive rate of 8.6 cy/ft./yr. at station D-20 (approximately 1,000 feet north of the FRF pier) to a negative rate of -2.4 cy/ft./yr. at station D-28 (located at the east end of Duck Landing Lane). Of the 16 profiles included in the South Monitoring Area, 4 of the 5 stations where the greatest positive density change rates were measured are located directly to the south of the Central Reach Area (D-19 through D-22), which is likely reflective of the positive impact the beach fill placement in the Central Reach Area has had along this section.

During the recent 25-month period, from April 2021 to May 2023, this area accreted at an average rate of +13.3 cy/ft./yr. Only one profile in the South Monitoring Area, located at station D-30 (Four Seasons Ln), experienced a negative volumetric change during this period. An examination of volume changes measured station to station shows the three of the four highest volumetric gains occurred at stations D-24, D-25, and D-26, respectively, as shown in Table 5. These three adjacent profiles are all just south of the USACE FRF property. The large gain in volume at these stations appears to be due to the filling in of a trough that was present in April 2021.

In Figure 6, the cumulative volumetric changes in the South Monitoring Area (green line) illustrates a relatively modest accretional trend between September 2013 and May 2015, prior to the construction of the project. This accretional trend resulted in a positive volumetric change of approximately 31,000 cy. A negative volumetric change was measured between December 2017 and June 2018, to the degree that in June 2018, the net volumetric change from the baseline survey in September 2013 to June 2018 was negative. From June 2018 to June 2020, the South Monitoring Area experienced a positive volumetric change of approximately 298,000 cy. The South Monitoring Area experienced a considerable negative volumetric change between June 2020 and April 2021. However, between April 2021 and May 2023, the Area experienced a positive volumetric change to the degree that in May 2023 the cumulative volumetric change was greater in May 2023 than had been measured at any other time since September 2013.

## VI. STORM DAMAGE VULNERABILITY ANALYSIS UPDATE

The May 2023 beach profile survey data was used to update the previously completed storm damage vulnerability analysis for the Town of Duck. The analysis utilized the Storm Induced Beach Change Model, SBEACH, developed by Larson and Kraus (Larson and Kraus, 1989) for the US Army Corps of Engineers (USACE). SBEACH is a two-dimensional model, that simulates changes in the beach profile that could result from coastal storms of varying intensity in terms of storm tide levels, wave heights, wave periods, and storm duration. Input data required by SBEACH includes beach cross-sections, the median sediment grain size, several calibration parameters, a temporally varying storm hydrograph (wave height, wave direction, wave period, and water surface elevation) and wind field (wind speed and direction).

The simulated beach profile changes that result from varying storm waves and water levels include the formation and movement of morphological features such as longshore bars, troughs, berms, and dunes. SBEACH assumes that the simulated profile changes are produced only by cross-shore processes, while longshore sediment transport processes are neglected. This empirically based numerical model was formulated using both field data and the results of large-scale physical model tests. Simulated profile changes are driven by the cross-shore variation in wave height and wave setup calculated at discrete points along the profile from the offshore zone to the landward survey limit.


The following basic assumptions underlie the SBEACH model:

- Breaking waves and variations in water level are the major causes of sand transport and profile response.
- The median sediment grain diameter along the profile is reasonably uniform across-shore.
- The shoreline is straight (i.e., longshore effects are negligible during the simulation term).
- Linear wave theory is applicable everywhere along the beach profile.

The SBEACH model was applied in the original Erosion and Shoreline Management Feasibility Study (CPE-NC, 2013) and the Town of Duck Erosion and Shoreline Management Engineering Design Report (CPE-NC, 2015). Detailed model setup and calibration information can be found in the original feasibility report (CPE-NC, 2015). The original feasibility study used beach profile data from 2013, and an update was conducted in 2016 (CPE-NC, 2016) using beach profile data from 2015. Another update was conducted in 2019 (APTIM, 2019), using beach profile data from May 2019. This report describes the latest update to assess storm vulnerability with SBEACH using the May 2023 survey as the initial condition.

During the design analysis for the initial Central Reach Beach Nourishment Project, an extensive analysis was completed to determine whether a scaled hurricane or nor'easter should be used for design purposes (CPE-NC, 2015). A review of historical data indicated that scaling all storm parameters to create synthetic storms results in conditions that do not represent natural occurrences. Using a method such as this may be appropriate for a quick study to investigate project feasibility but could ultimately result in over- or underestimation of project need and performance. As a result, actual storm characteristics were reviewed to select storms that best matched extreme event characteristics. Considering that the storm hydrograph is the primary model driver, the top wave height and storm surge events were compared with the calculated return period descriptors. The Perfect Storm best represented a 3-year event, Hurricane Sandy resembled a 5-year event, and Hurricane Isabel may best describe a 25-year event. Considering the project's goal was to provide a reasonable level of storm damage reduction, Hurricane Isabel was adopted as the design storm.

To ensure consistency with the previous SBEACH studies conducted in the Central Reach Project Area, the 2023 analysis used the same Hurricane Isabel storm characteristics as used in the previous vulnerability assessments conducted for the Town of Duck. The only modification was to update the water level to 2023



to account for the relative sea level rise. The increase in water level was calculated based on the relative sea level rise rate measured at the NOAA Tide Gauge (Station ID 8651370) located at the USACE FRF Pier in Duck, NC and multiplying that rate by 20 years (the time elapsed since Hurricane Isabel's landfall in North Carolina), to represent the water level if the hurricane impacted the area in 2023.

The results of the SBEACH simulations were used to identify structures that could be impacted during the design storm events. A 1-foot change in profile elevation is a reasonable threshold for estimating when structures become vulnerable to wave damage, including undermining and/or inundation (USACE, 1985). Therefore, a structure was considered vulnerable if any part of the structure was seaward of the landward most location where the profile was lowered by 1 foot. For this study, the landward most location where the profile was lowered by 1-foot was extracted from model results along profiles to identify the impact points. These impact points were then connected to create an impact line that was used to identify structures damaged between profiles. The resulting May 2023 impact lines are shown on the maps included in Appendix C. For comparison purposes, the impact lines developed during the May 2019 vulnerability analysis are also shown on the maps.

As summarized in Table 6, the updated May 2023 analysis showed that no structures and only 9 pools were shown to be vulnerable as defined herein. Compared to the results of the May 2019 vulnerability analysis, this represents a reduction of 29 structures and 32 pools that were shown as vulnerable during the previous vulnerability analysis. In May 2019, the analysis of the area north of the USACE FRF property identified 1 structure and no pools as vulnerable within the North Monitoring Area (D-1 to D-10), while 0 structures or pools were identified as vulnerable within the Central Reach Project Area (D-10 to D-19). According to the updated analysis of the May 2023 conditions, no structures or pools were identified as vulnerable within the North Monitoring Area or within the Central Reach Project Area as shown in Table 6.

The volume change between the May 2019 and May 2023 monitoring events for the North Monitoring Area (D-01 to D-10) indicated that this area experienced a volumetric gain over the 4-year period. The results indicated that between May 2019 and May 2023, the North Monitoring Area gained an average 15.6 cy/ft., or approximately 143,800 cubic yards, over the 4-year period.

The 2023 analysis of the Town of Duck shoreline south of the USACE FRF property (D-23 to D-34) indicated a significant reduction in the number of identified vulnerable structures compared to the results of the 2019 analysis. While 28 structures were identified as vulnerable in the 2019 analysis, 0 structures were identified based on 2023 conditions. Similarly, the total number of pools identified as vulnerable south of the USACE FRF in 2023 was 9, a reduction of 78% compared to the 40 pools identified as vulnerable based on 2019 conditions.

The volume change between the May 2019 and May 2023 monitoring events for the South Monitoring (D-19 to D-34) areas indicated that this area also experienced volumetric gains over the 4-year period. Between May 2019 and May 2023, the South Monitoring Area gained, on average, 19.7 cy/ft., or approximately 268,000 cy. Most of those structures identified as impacted in the 2019 analysis were located at the south end of Duck, between stations D-25 (100 ft. south of Old Duck Rd) and D-34 (southern Town boundary), a total distance of approximately 8,820 feet. Between May 2019 and May 2023, a positive volumetric change of approximately 139,000 cy was measured, or an average 15.5 cy/ft, across the active profile (above -24 ft NAVD88).

**Table 6. Storm Damage Vulnerability – Existing Conditions**

Monitoring Stations		May 2019 Conditions		May 2023 Conditions	
From	To	Structure	Pool	Structure	Pool
D-01	D-02	0	0	0	0
D-02	D-03	0	0	0	0
D-03	D-04	0	0	0	0
D-04	D-05	1	0	0	0
D-05	D-06	0	0	0	0
D-06	D-07	0	0	0	0
D-07	D-08	0	0	0	0
D-08	D-09	0	0	0	0
D-09	D-10	0	0	0	0
D-10	D-11	0	0	0	0
D-11	D-12	0	0	0	0
D-12	D-13	0	0	0	0
D-13	D-14	0	0	0	0
D-14	D-15	0	0	0	0
D-15	D-16	0	0	0	0
D-16	D-17	0	0	0	0
D-17	D-18	0	0	0	0
D-18	D-19	0	0	0	0
D-19	D-20	0	0	0	0
D-20	D-21	0	0	0	0
D-21	D-22	0	0	0	0
D-22	D-23	0	0	0	0
D-23	D-24	0	1	0	0
D-24	D-25	0	0	0	0
D-25	D-26	1	0	0	0
D-26	D-27	0	3	0	0
D-27	D-28	1	6	0	0
D-28	D-29	13	7	0	0
D-29	D-30	4	7	0	0
D-30	D-31	0	3	0	0
D-31	D-32	3	7	0	3
D-32	D-33	5	4	0	3
D-33	D-34	1	2	0	3
<b>D-01</b>	<b>D-34</b>	29	40	0	9

Note that this analysis only identified which structures could experience damage due to storm-induced erosion caused by a storm with predetermined storm characteristics that mimic those measured during Hurricane Isabel. The analysis did not include an evaluation of damages due to flooding, wave impacts, or wind nor does it quantify the economic impacts resulting from the damage or loss of such structures.