MIAMI-DADE COUNTY, FLORIDA

COASTAL STORM RISK MANAGEMENT

Integrated Feasibility Study and Environmental Assessment

APPENDIX A
Engineering

November 2021

U.S. ARMY CORPS OF ENGINEERS
JACKSONVILLE DISTRICT

US Army Corps of Engineers ®
Jacksonville District

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1 BACKGROUND

Infrastructure along the Miami-Dade County, Florida shoreline is vulnerable to damage from erosion, flooding and waves caused by coastal storms. This study investigates alternatives that address these vulnerabilities for portions of the previously authorized Main Segment of the Miami-Dade County Beach Erosion Control and Hurricane Protection (BEC&HP) Project including the municipalities of The Village of Bal Harbour, The Town of Surfside, and the City of Miami Beach (reference the Limited Re-evaluation Report (LRR); (USACE 2016)). The study also includes the barrier island of Key Biscayne but excludes both Haulover Park, which was part of the Main Segment of the BEC project, and the Sunny Isles Segment of the BEC&HP Project. The study also excludes Golden Beach, Fisher Island, and Virginia Key, as explained in Section 3.

2 PURPOSE

The purpose of this report is to assess potential solutions to erosion problems and potential storm damage susceptibility along 13.4 miles of Miami-Dade County, Florida (Figure A-1). The study area includes the barrier island between Bakers Haulover Inlet in the north and Government Cut in the south. This segment is 9.3 miles long and stretches between Florida Department of Environmental Protection (FDEP) reference monuments R-27 and R-74. Additionally, 4.1 miles of the island of Key Biscayne (R-92 to R-113) is also being evaluated. Key Biscayne is approximately 2.7 miles south of Government Cut.

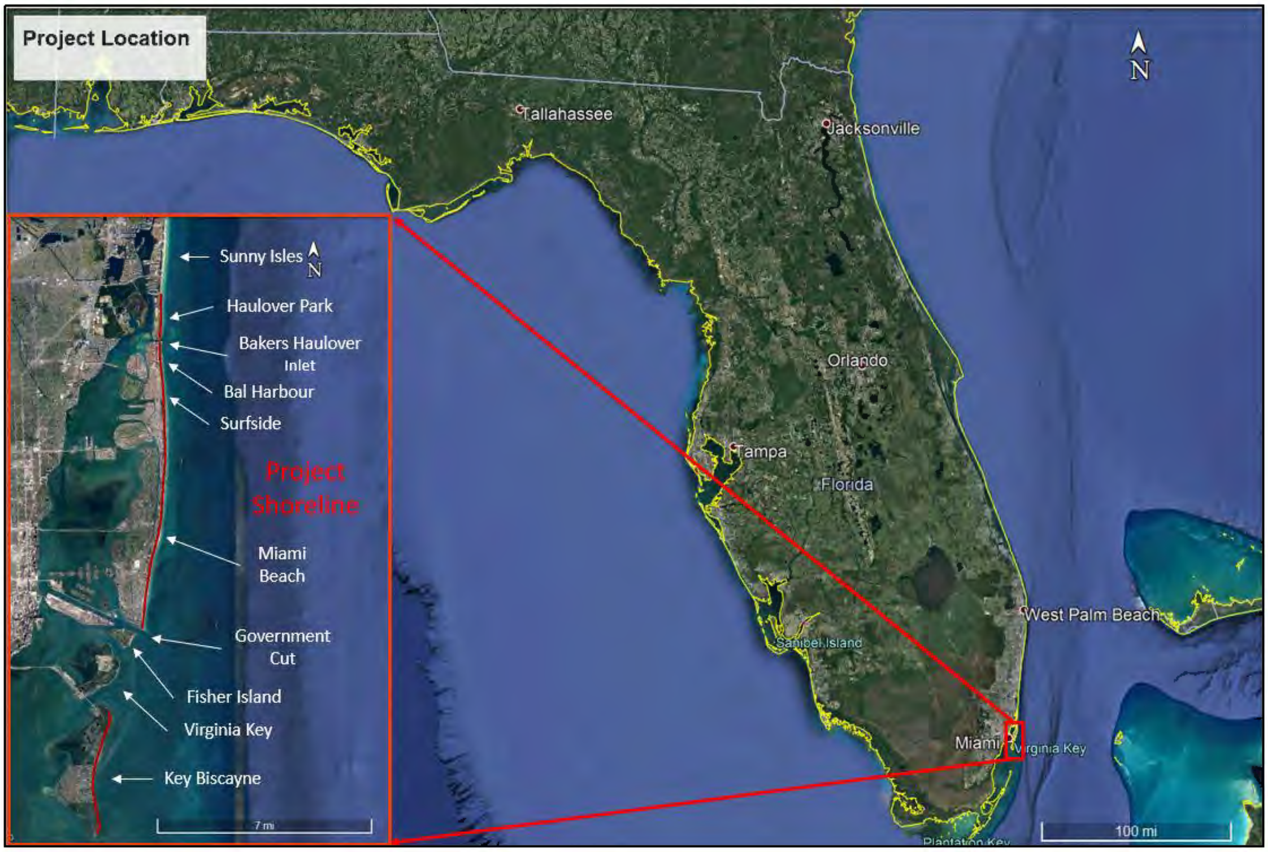


Figure A-1. Project Site

3 PREVIOUS PROJECT HISTORY

Section 203 of the Flood Control Act of 1968 authorized the BEC&HP Project for Dade County Florida. In addition, Section 69 of the 1974 Water Resources Development Act (Public Law 93-251) modified the authorized project and authorized initial construction by non-Federal interests, as well as subsequent nourishments by Federal or non-Federal interests, of the 0.85-mile segment along Bal Harbour Village, immediately south of Bakers Haulover Inlet. The authorized project, as described in the 1968 Chief's Report for the project, provided for the construction of a protective and recreational beach and a protective dune for 9.3 miles of shoreline between Government Cut and Bakers Haulover Inlet (encompassing Miami Beach, Surfside, and Bal Harbour) and for the construction of a protective and recreational beach along 1.2 miles of shoreline at Haulover Beach Park just north of Bakers Haulover Inlet.

The Sunny Isles portion of the project was added in 1985 and initially constructed in 1988. Specifically, the Supplemental Appropriations Act of 1985 (Public Law 99-88) and Section 501 of the Water Resources Development Act of 1986 (Public Law 99-662) authorized the BEC&HP Project for Dade County, Florida, north of Haulover Beach Park. However, only the authority of the Supplemental Appropriations Act of 1985 has been implemented through the execution of a local cost sharing agreement. This authorization provides for modification of the authorized 1968 BEC&HP for Dade County, Florida to provide for the construction and periodic nourishment of a protective beach along the 2.5 miles through Sunny Isles and for the extension of the period of Federal participation in the cost of nourishing the existing Dade County BEC&HP from 10 years to the present end of Federal participation, 50 years from initial construction, or 2025 for the Main Segment and 2038 for the Sunny Isles segment.

In the current analysis, the Sunny Isles segment (FDEP Range Monument R-7 to R-19.3) is not considered as the period of Federal participation extends an additional 13 years beyond that of the originally constructed project. Additionally, the 1.2 miles of shoreline at Haulover Beach Park (R-19.3 to R-26.7) has been screened out of the analysis due to the accretional nature of that shoreline. Golden Beach, at the northern end of Miami-Dade County (R-1 to R-7), was screened out because the shoreline in this area is stable due to the material it receives from the adjacent beach projects at Sunny Isles to the south and Broward County Segment III to the north. Fisher Island (R-75 to R-78) and Virginia Key (R-79 to R-88) were screened out due to the lack of public interest in these areas. Key Biscayne (R-89 to R-113) was also initially screened out of the analysis due the lack of public access.

A waiver was granted during the study process to increase the length of the study from three years to four years. As a result of the increased study length and due to the local sponsor committing to increasing public access, Key Biscayne was reintroduced into the study analysis. The 4.1-mile length of

Key Biscayne and the 9.3-mile of shoreline between Bakers Haulover Inlet and Government Cut (Main Segment, R-27 to R-74) are the focus of the analysis described in this appendix.

3.1 HISTORY OF MAIN SEGMENT

The Main Segment was initially constructed over a period of events between 1975 and 1982. Current authorization is for a dune 20 feet wide at 11.5 feet above mean low water (MLW) and a level berm 50 feet wide at elevation nine feet MLW with natural slopes as shaped by wave action. As authorized, the Main Segment did not have a recommended renourishment interval, but the project was intended to be nourished periodically as needed to compensate for erosion losses throughout the 50-year period of Federal participation. Figure A-2 provides a timeline of construction and renourishment events for the Bal Harbour and Surfside segments.

Figure A-3. shows graphically the limits of previous Federal and non-Federal construction activities and provides a table of volumes and sand sources. As shown in the figures, there have been numerous nourishment events in Bal Harbour. Many of these are small-volume placements associated with maintenance dredging of the Atlantic Intracoastal Waterway. Miami-Dade County has also constructed two small truck-haul projects, one in Bal Harbour and one in Surfside to offset erosional losses.

To the south of this area within the City of Miami Beach, there have been numerous nourishment events focused on a few hotspots. Figure A-4 provides a timeline of construction and renourishment events for this segment.

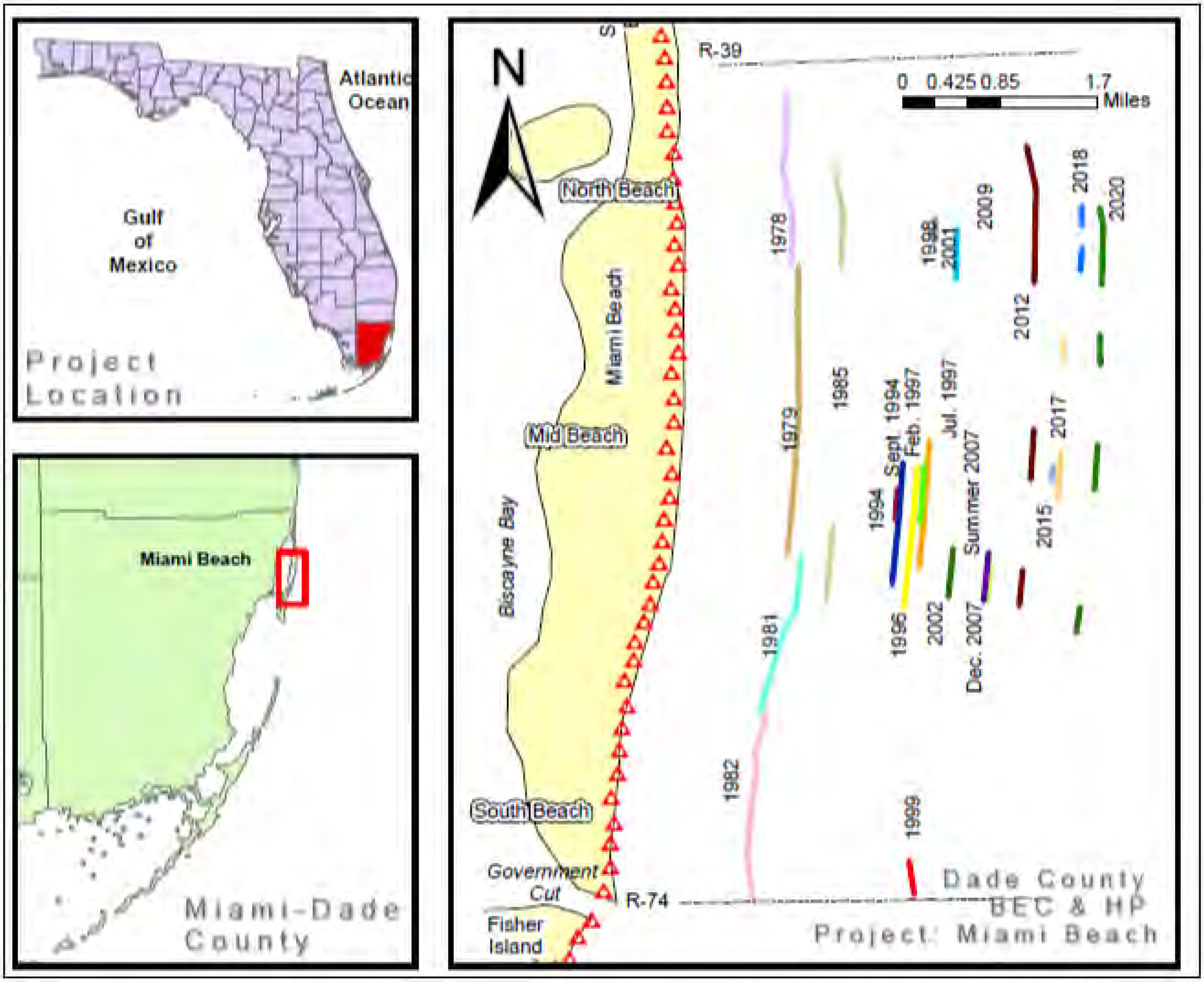


Figure A-5 graphically shows the limits of previous placements and provides a table (Table A-1) of volumes and sand sources. Within this segment, the renourishment events have been focused on a few hotspot locations with large stretches of the coast absent of renourishment events since initial construction. Miami-Dade County has also constructed many smaller nourishment events within this stretch. The county also constructed three shore-connected emergent breakwaters near R-59 to R-60 to alleviate a hotspot in this area due to a change in shoreline orientation.

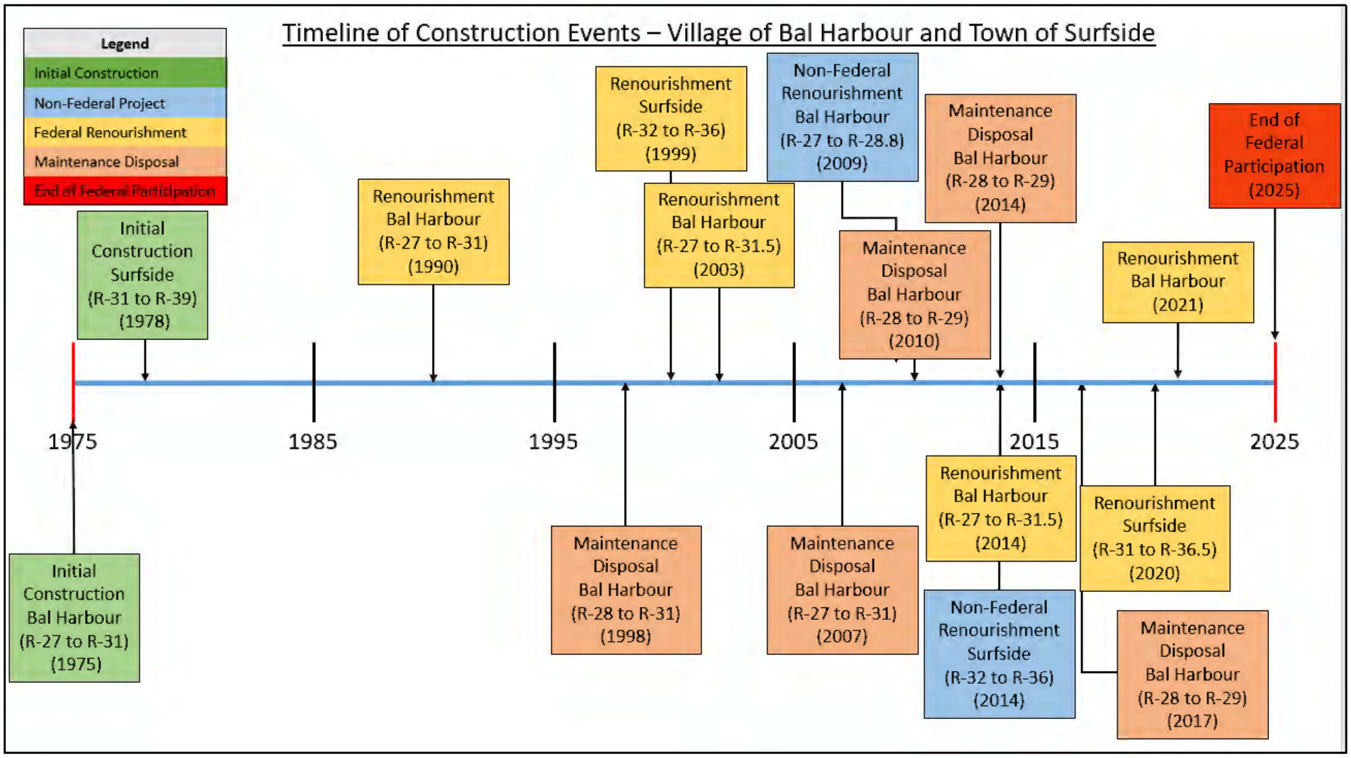


Figure A-2. Timeline of Bal Harbour and Surfside History

Main Segment – Bal Harbour Beach Projects

Line Color	Project Type	Construction Date	Event Type	Location Name	Location R-mons	Volume (cy)	Activity/Borrow Source	Length (miles)
	USACE	1975	Initial Construction	Bal Harbour Beach	R-27 to R-31	1,625,000	Offshore Borrow Areas A, B & C	0.8
	USACE	1990	Renourishment	Bal Harbour Beach	R-27 to R-31	225,000	Unspecified Offshore Borrow Area	0.8
	USACE	1998	Maintenance Disposal	Bal Harbour Beach	R-28 to R-31	35,000	Bakers Haulover Inlet & Flood Shoal & AIWW	0.6
	USACE	2003	Renourishment	Bal Harbour Beach	R-27 to R-31.5	188,000	Bakers Haulover Ebb Shoal	0.85
	USACE	2007	Maintenance Disposal	Bal Harbour Beach	R-27 to R-31	30,000	AIWW	0.8
	Local	2009	Renourishment	Bal Harbour Beach	R-27 to R-28.8	15,000	Truck Haul Ortona Mine	0.35
	USACE	2010	Maintenance Disposal	Bal Harbour Beach	R-28 to R-29	33,080	Bakers Haulover Flood Shoal & AIWW	0.2
	USACE	Jan. 2014	Renourishment	Bal Harbour Beach	R-27 to R-31.5	235,733	Bakers Haulover Ebb Shoal	0.85
	USACE	Mar. 2014	Maintenance Disposal	Bal Harbour Beach	R-28 to R-29	49,592	AIWW Cut DA-9	0.2
	USACE	2017	Maintenance Disposal	Bal Harbour Beach	R-28 to R-29	37,000	AIWW	0.2

Main Segment – Surfside Beach Projects

Line Color	Project Type	Construction Date	Event Type	Location Name	Location R-mons	Volume (cy)	Activity/Borrow Source	Length (miles)
	USACE	1978	Initial Construction	Surfside Beach	R-31 to R-39	2,640,000	Offshore Borrow Areas A, B & C	1.7
	USACE	1999	Renourishment	Surfside Beach	R-32 to R-36	590,000	South of Government Cut Offshore B.A.	0.8
	Local	2014	Renourishment	Surfside Beach	R-32 to R-36	12,800	Truck Haul from nearby construction excavation	0.8
	USACE	2020	Renourishment	Surfside Beach	R-31 to R-36.5	325,000	Truck Haul from Vulcan Witherspoon Mine	1.1

Figure A-3. Map of Previous Bal Harbour and Surfside Nourishment Events and Tabulated Volumes

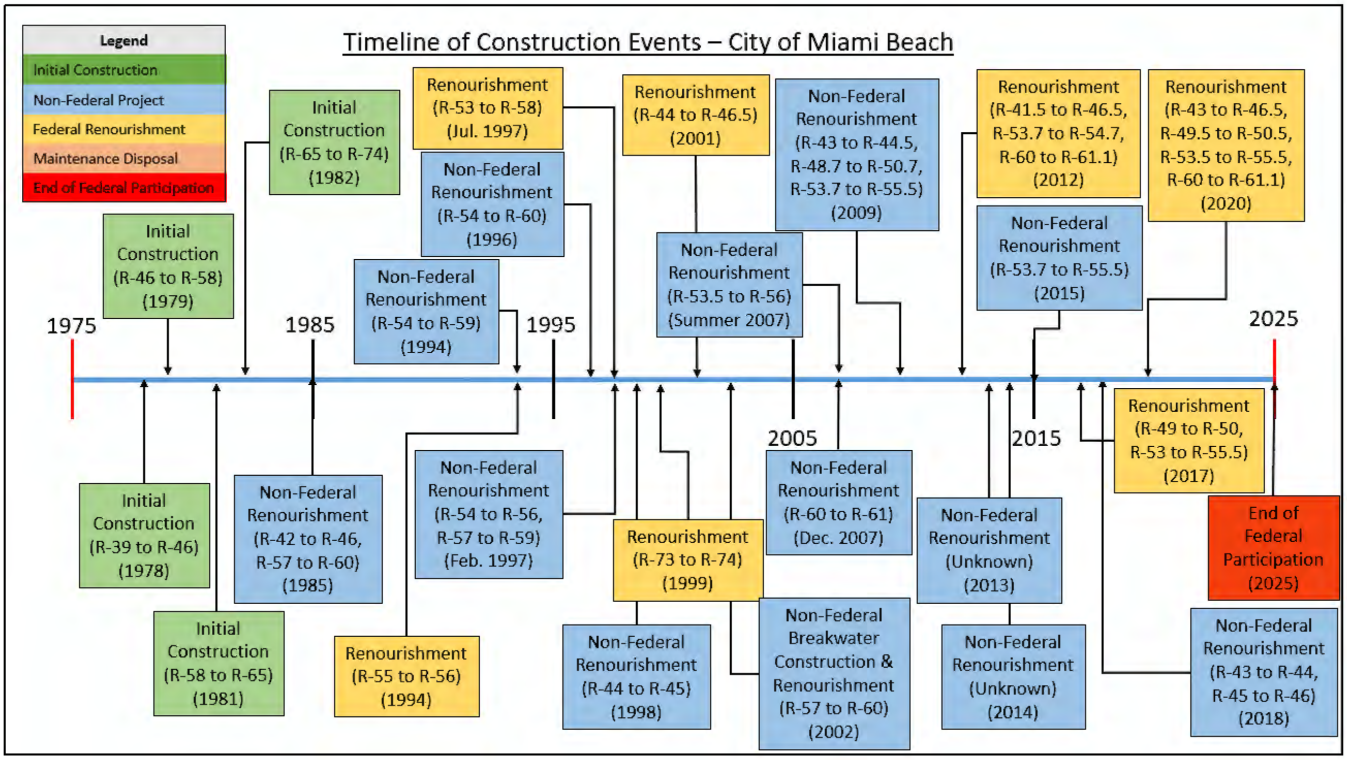


Figure A-4. Timeline of Miami Beach History

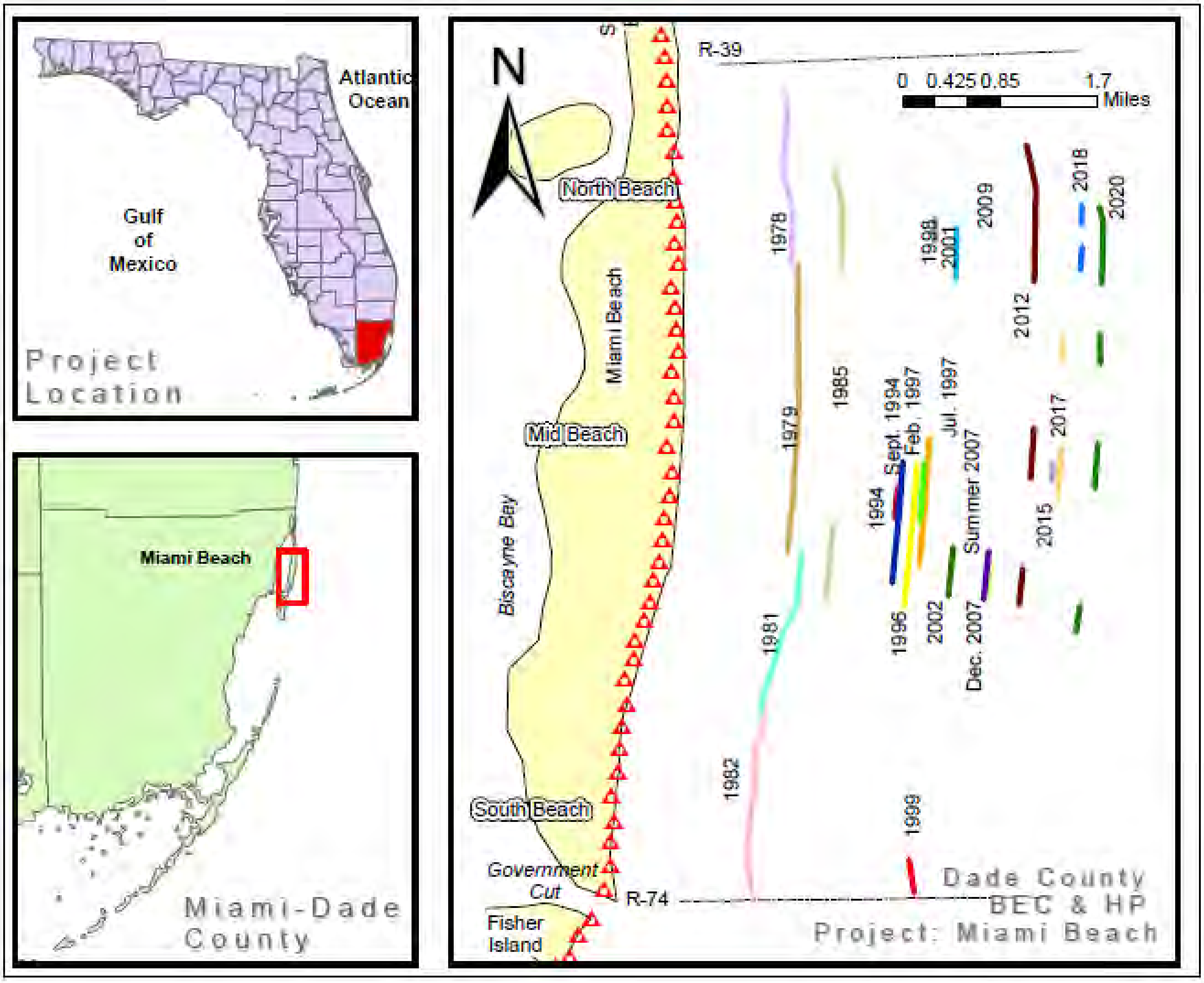


Figure A-5. Map of Previous Miami Beach Renourishment Events and Tabulated Volumes

Table A-1. Table of Previous Miami Beach Renourishment Events and Tabulated Volumes

Line Color	Project Type	Construction Date	Event Type	Location		Volume (cy)	Activity/Borrow Source	Length (miles)
				Name	R-mons			
	USACE	1978	Initial Construction (Phase II)	North Beach	R-39 to R-46	1,530,000	Offshore Borrow Area D	1.5
	USACE	1979	Initial Construction (Phase III)	Mid Beach	R-46 to R-58	3,177,100	Offshore Borrow Areas D & E	2.4
	USACE	1981	Initial Construction (Phase IV)	Mid Beach	R-58 to R-65	2,200,000	Offshore Borrow Area E	1.4
	USACE	1982	Initial Construction (Phase V)	South Beach	R-65 to R-74	2,400,000	Offshore Borrow Area E & 5th Contract Borrow Area	1.9
	Local	1985	Renourishment	Mid Beach	R-42 to R-46 & R-57 to R-60	110,000 & 50,000	Unknown	0.8 & 0.6
	USACE	Sept. 1994	Renourishment	Mid Beach	R-55 to R-56	122,096	Borrow Area #1, offshore Golden Beach	0.2
	Local	1994	Renourishment	Mid Beach	R-54 to R-59	30,000	Truck Haul from upland source	1.0
	Local	1996	Renourishment	Mid Beach	R-54 to R-60	8,000	Truck Haul from South Beach	1.2
	Local	Feb. 1997	Renourishment	Mid Beach	R-54 to R-56 & R-57 to R-59	35,000 & 50,000	Truck Haul from CSR Rinker laker fill material &	0.8
	USACE	Jul. 1997	Renourishment	Mid Beach	R-53 to R-58	478,938	Borrow Area #1, offshore Golden Beach	1.0
	Local	1998	Renourishment	North Beach	R-44 to R-45	18,000	Truck Haul from upland source	0.2
	USACE	1999	Renourishment	South Beach	R-73 to R-74	132,000	South of Government Cut Offshore Borrow Area	0.3
	USACE	2001	Renourishment	North Beach	R-44 to R-46.5	167,662	South of Government Cut Offshore Borrow Area	0.5
	Local	2002	Breakwater Construction	Mid Beach	R-57 to R-60	125,000	Truck Haul from South Beach to Backfill construction of 32nd St. Breakwaters	0.5
	Local	Summer 2007	Renourishment	Mid Beach	R-53.5 to R-56	70,000	Truck Haul from South Beach	0.5
	Local	Dec. 2007	Renourishment	Mid Beach	R-60 to R-61	30,000	Truck Haul from upland source	0.2
	Local	2009	Renourishment	North and Mid Beach	R-43 to R-44.5 & R-48.7 to R-50.7 & R-53.7 to R-55.5	10,000 & 10,000 & 3,000	Truck Haul from upland source	0.9
	USACE	2012	Renourishment	North Beach	R-41.5 to R-46.5 & R-53.7 to R-54.7 & R-60 to R-61.1	206,402 & 122,237 & 18,922	South of Government Cut Offshore Borrow Area & Truck Haul from South Beach	1.5
	Local	2013	Renourishment	Mid Beach	Unknown	6,296	Truck Haul from upland source	Unknown
	Local	2014	Renourishment	Mid Beach	Unknown	31,365	Truck Haul from upland source	Unknown
	Local	2015	Renourishment	Mid Beach	R-53.7 to R-55.5	19,259	Truck Haul from upland source	0.3
	USACE	2017	Renourishment	Mid Beach	R-49 to R-50 & R-53 to R-55.5	83,665 & 149,665	Truck Haul from Vulcan Witherspoon Mine	0.7
	Local	2018	Renourishment	North Beach	R-43 to R-44 & R-45 to R-46	12,500 & 14,400	Truck Haul from upland source	0.4
	USACE	2020	Renourishment	Mid Beach	R-43 to R-46.5 & R-49.5 to R-50.5 & R-53.5 to R-55.5 & R-60 to R-61	25,000 & 78,800 & 68,400 & 100,900	Truck Haul from Garcia Mine	1.5

3.2 HISTORY OF KEY BISCAYNE

Key Biscayne has periodically received beach nourishments since 1969. Figure A-6 provides a timeline of nourishment events for Key Biscayne and Figure A-7 shows the limits of the previous construction activities for the Miami-Dade barrier islands, including Key Biscayne, Virginia Key, and Fisher Island. Section 101 of the River and Harbor Act of 1962 (Public Law 87-874) authorized the Beach Erosion Control Report on Cooperative Study of Virginia and Biscayne Keys, Florida (House Document Number 561, 87th Congress, Second Session), recommending federal participation in a beach nourishment project on portions of Virginia Key and Key Biscayne. In 1969 a 50-foot-wide berm at 7 feet NGVD was restored along R-92.5 to R-96 and R-99 to R-101. In 1985, a small beach erosion control project for Key Biscayne was approved under Section 103 of the River and Harbor Act 1962. The project was a Section 103 project through the Continuing Authorities Program (CAP) that provided for a one-time restoration along portions of Key Biscayne. The project restored 2.4 miles (excluding R-111 to R-112.3) with 420,000 cubic yards (cy) of sand from an offshore borrow area located one mile southeast of Cape Florida. The project restored a 25-foot-wide berm at Key Biscayne and a 20-foot-wide berm at Cape Florida State Park, both at elevation 7 feet-MLW, and provided seven years of advance nourishment. Since then, several local nourishment projects have occurred at Key Biscayne (2002, 2008, 2012, and 2017).

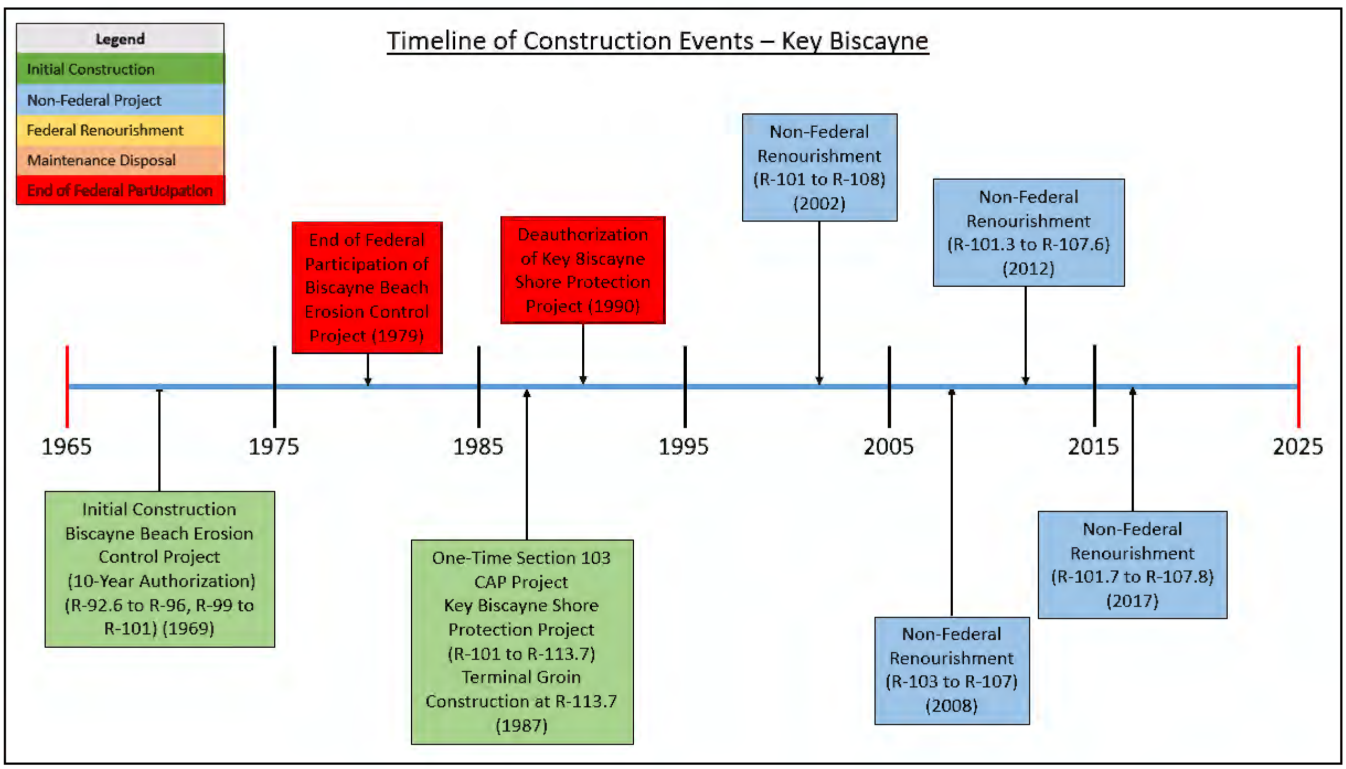
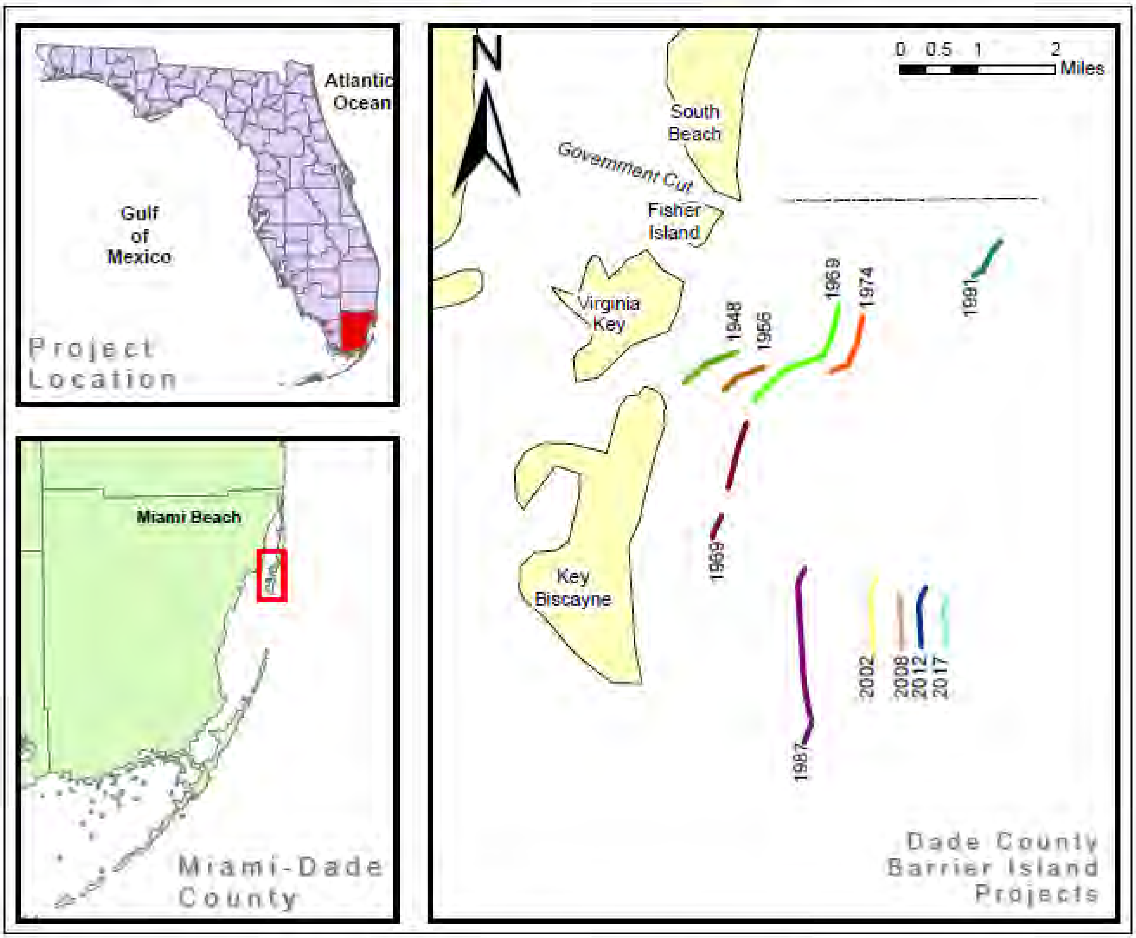


Figure A-6. Key Biscayne Beach Nourishment History



Line Color	Project Type	Construction Date	Event Type	Location		Volume (cy)	Activity/Borrow Source	Length (miles)
				Name	R-mons			
	USACE	1948	Groin Construction	Virginia Key Bear Cut Inlet Shoreline	R-84 to R-87	0	Construction of Timber Groins inside Bear Cut Inlet	0.6
	USACE	1956	Groin Construction	Virginia Key Bear Cut Inlet Shoreline	R-84 to R-87	0	Construction of Timber Groins inside Bear Cut Inlet	0.6
	USACE	1965	Groin Construction	Virginia Key Bear Cut Inlet Shoreline	Unknown	0	Construction of concrete pilings and wood panel groins	Unknown
	USACE	1969	Initial Construction	Virginia Key Beach	R-79 to R-88	176,800	Offshore Borrow Area	1.3
	USACE	1969	Initial Construction	Biscayne Beach	R-92.6 to R-96 & R-99 to R-101	196,300	Offshore Borrow Area	0.6 & 0.4
	USACE	1974	Renourishment/Groin Construction	Virginia Key Beach	R-79 to R-84	110,000	Dredge material from Government Cut. Groins Constructed.	0.9
	USACE	1987	Renourishment/Groin Construction	Biscayne Beach	R-101 to R-113.7	420,000	Offshore Borrow Area near Cape Florida. Terminal Groin Constructed at R-113.7	2.4
	Private	1991	Initial Construction/Groin	Fisher Island	R-75 to R-78	25,000	Imported aragonite sand and construction of 8 groins	0.6
	Local	2002	Renourishment	Biscayne Beach	R-101 to R-108	121,000	Offshore Borrow Area near southern tip of Key Biscayne	1.3
	Local	2003	Groin Construction/Rehab	Virginia Key Beach	Unknown	Unknown	Rehab of existing groins and construction of 3 new groins with small amount of fill	Unknown
	Local	2008	Renourishment	Biscayne Beach	R-103 to R-107	2,400	Upland	0.7
	Local	2012	Renourishment	Biscayne Beach	R-101.3 to R-107.6	37,500	Upland	1.1
	Local	2017	Renourishment	Biscayne Beach	R-101.7 to R-107.8	27,000	Upland	1.1

Figure A-7. Map of Previous Miami-Dade County Barrier Island (Key Biscayne, Virginia Key, and Fisher Island) Renourishment Events and Tabulated Volumes

4 NATURAL FORCES

4.1 WINDS

Local winds are the primary means of generating the small-amplitude, short-period waves that are an important mechanism of sand transport along the Florida shoreline. The project shoreline in Miami-Dade County lies between approximately 25.6° and 25.9° latitude, slightly south of the northern boundary of the tropical trade wind zone. Typical prevailing winds are from the east.

Wind data offshore of the project area is available from the U.S. Army Corps of Engineers (USACE) Wave Information Study (WIS) Program. Wind forcing in WIS applies the 10-meter (33 ft) wind fields from the National Centers for Environmental Predictions and National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al. 1996). For significant storm events the reanalysis winds are enhanced using statistical downscaling, assimilation of in situ and satellite wind data, and dedicated analysis of significant tropical and extra-tropical storms systems (Hesser et al. in preparation). In the Atlantic Basin, the WIS hindcast database covers a 35-year period of record extending from 1980 to 2014.

There are 565 WIS stations along the Atlantic Coast of the United States. WIS Station 63470 is representative of offshore wind and wave conditions for the project area as this is located offshore of the center of the project area. Table A-2 provides a summary of wind data from WIS Station 63470, located at latitude 25.83 N and longitude -79.92 E (approximately 12.5 miles east of the project area at a depth of 1,040 feet, MSL). This table contains a summary of average wind speeds and frequency of occurrence broken down into eight 45-degree angle-bands. Annual average winds are predominantly from the east with the strongest average wind speed coming from the northeast. The wind rose presented in Figure A-8 provides a further breakdown of winds in the project area.

Table A-2. Average Wind Conditions

Wind Direction (from)	WIS Station #63470 (1980 - 2014)	
	Percentage Occurrence (%)	Average Wind Speed (mph)
North	7.8	14.7
Northeast	15.8	15.1
East	32.7	13.5
Southeast	19.7	11.5
South	9.2	11.3
Southwest	5.0	11.5
West	4.1	12.8
Northwest	5.7	15.1

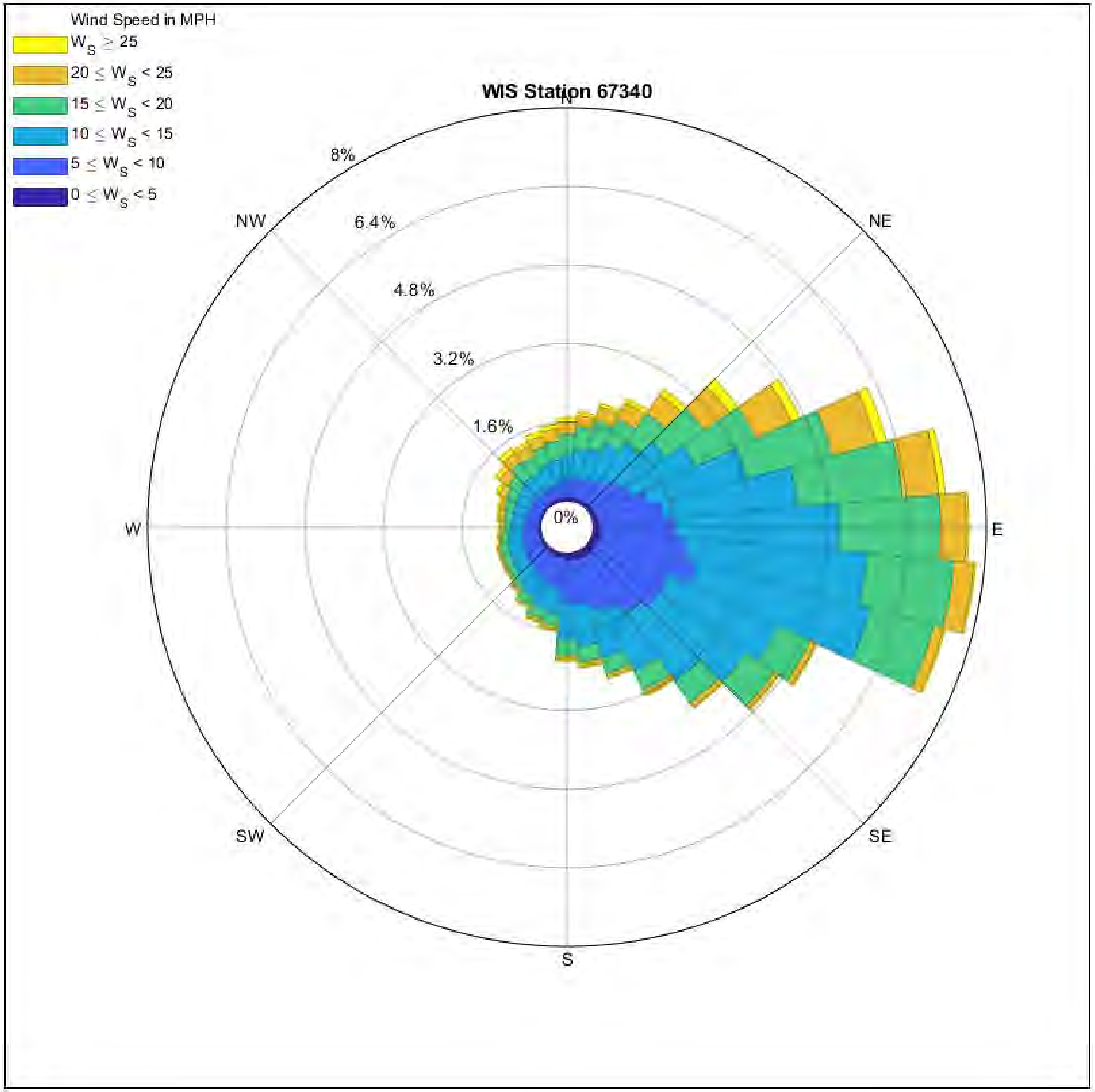


Figure A-8. Wind Rose - WIS Station 67340

Wind conditions in Coastal Florida are seasonal. A further breakdown of the wind data provides a summary of the seasonal conditions (Table A-3). From November through March, frontal weather patterns driven by cold Arctic air masses can extend as far as South Florida. These events (referred to as "Nor'easters") generate winds that are predominantly from the east or northeast quadrant. Nor'easters often result in wave conditions that cause extensive beach erosion on the east coast of Florida. Typically, along the southeast coast of Florida the wave conditions lessen as you move south due to the wave blocking effects of the Bahamas. Even with these effects, Miami-Dade County can experience significant erosion and storm conditions due to these Nor'easters.

During late spring, summer, and early fall months (April through October) cold frontal passage is rare in south Florida. The predominant trade winds lead to winds of lesser strength coming from the east and southeast. The area is subject to the impacts from tropical storms throughout hurricane season with rare occurrences of tropical events impacting the area outside of the Atlantic hurricane season. Tropical storms and hurricanes can generate devastating winds, waves, and storm surge in the area. These intense seasonal events will be discussed in greater detail under Section 4.4: Storm Effects. Near Miami-Dade County, summer winds are predominantly from the east. In the fall, winds shift to the east and northeast.

In addition to storm winds, the project area also experiences daily breezes. These onshore and offshore winds result from differential heating of land and water masses and typically blow perpendicular to the shoreline. While these breezes play a significant role in local weather patterns, they are not an appreciable cause of sediment movement in the nearshore.

Table A-3. Seasonal Wind Conditions

Month	WIS Station #67340 (1980 - 2014)	
	Average Wind Speed (mph)	Predominant Direction (from)
January	15.1	NE
February	14.6	E
March	14.9	E
April	13.7	E
May	12.4	E
June	10.8	SE
July	10.7	SE
August	10.7	SE
September	11.3	E
October	13.9	NE
November	15.8	NE
December	15.1	NE

4.2 WAVES

Energy dissipation that occurs as waves enter the nearshore zone and break is the principal method of sediment transport. Wave height and period, in combination with tides and storm surge, are the most important factors influencing the behavior of the shoreline. The Miami-Dade County study area is exposed to both short period wind-waves and to longer period open-ocean storm swells (Nor'easters and tropical storm events). As mentioned previously, the Bahamas islands and Bahama Banks limit some of the exposure of the area to long period waves from distant storms. However, due to the steepness of the continental shelf in the area, long-period waves that reach the area can hold significant height close to shore.

Wave data for this report were obtained from the USACE WIS hindcast database for the Atlantic Ocean. For this basin WIS uses the third-generation spectral wave model WAVEWATCH III (Tolman, 2014) to estimate the growth, propagation, and dissipation of ocean waves due to wind forcing. As previously discussed, WIS station 67340 was selected for the study. Given the relatively deep depth at this station (1,040 feet, MSL) and the steep change in depth between the station and shoreline, wave conditions at station 63470 are likely higher than the nearshore wave conditions which are altered by shoaling and a nearshore reef system. Nevertheless, the WIS data provides good insight into the frequency of high-energy events impacting the area.

Table A-4 summarizes the percentage of occurrence and average wave height of the WIS waves by direction. Average wave heights range from 1.0 foot to 2.3 feet, indicating a generally mild wave climate year-round. Wave directions are generally from the northeast in the winter months and east and southeast in the milder months. This can be seen in greater detail in the wave rose presented in Figure A-9. A seasonal breakdown of wave heights shows that higher wave heights are more frequent in the fall and winter months (November through March) and tend to originate from the northeast quadrant (Table A-4). Spring, summer, and early fall waves (April through October) are smaller and originate predominantly from the east and southeast.

Table A-5 provides a seasonal breakdown of percent occurrence by wave period. From this table, it can be seen that short period, locally generated wind-waves are common throughout the year. The yellow highlighted values show the dominant wave period for each month. These are generally between four and five seconds outside of the summer months where the dominant period is shorter and averages under four seconds.

Table A-4. Seasonal Wave Conditions

Month	WIS Station 63470 (1980-2014)	
	Average Wave Height (feet)	Predominant Direction (from)
January	2.1	NE
February	2.0	NE
March	2.0	NE
April	1.7	E
May	1.5	E
June	1.0	SE
July	1.0	SE
August	1.0	E
September	1.3	E
October	1.9	NE
November	2.3	NE
December	2.1	NE

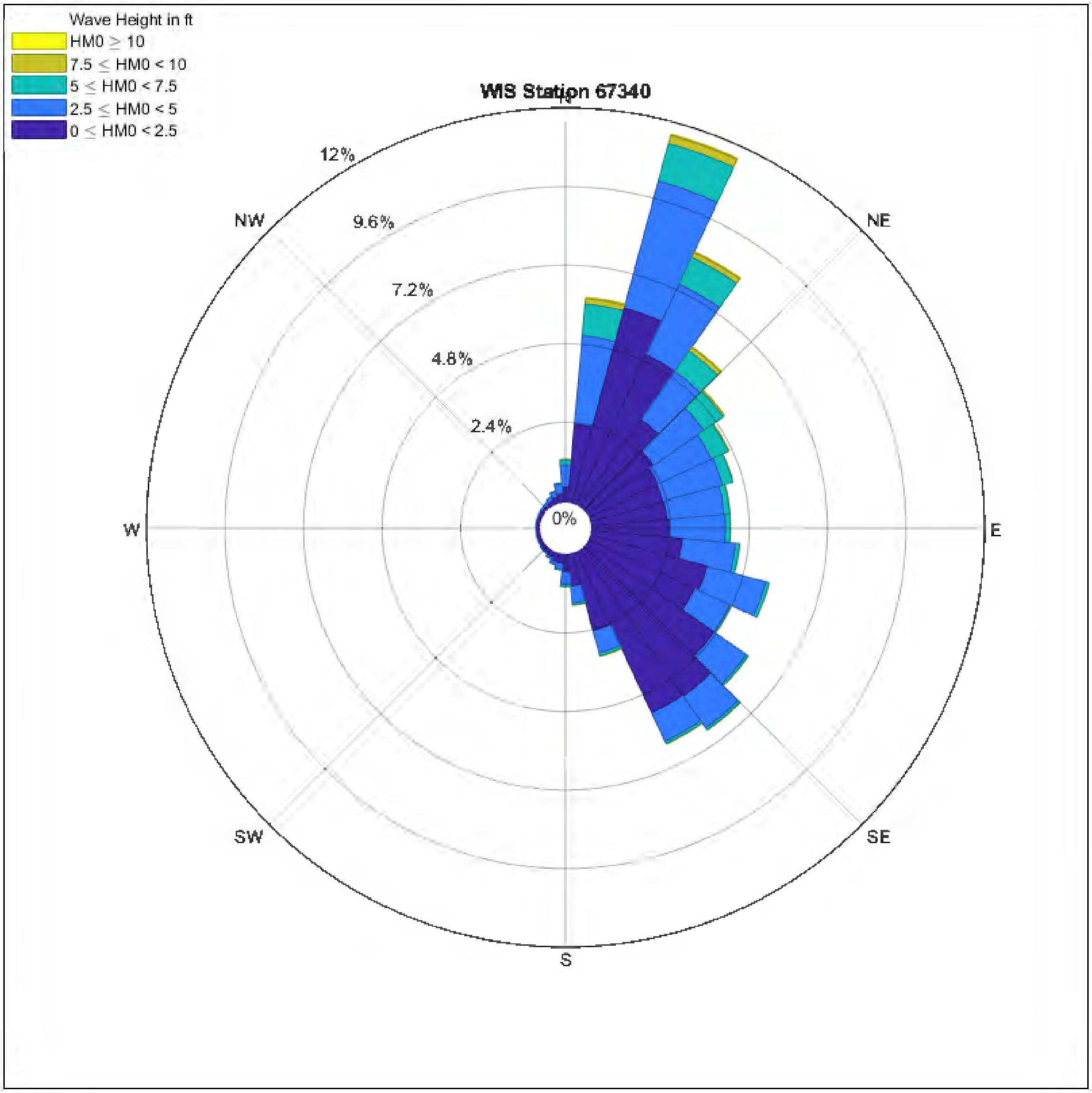


Figure A-9. Wave Rose - WIS Station 63470

Table A-5. Wave Period - Percent Occurrence with Maximum Values Highlighted in Yellow

Wave Period	Percent Occurrence by Wave Period Band											
(Sec)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
< 4.0	12.0	10.6	11.0	13.3	20.8	32.0	35.8	31.3	22.0	11.8	9.8	9.9
4.0 - 4.9	19.6	20.1	22.7	27.4	28.6	28.4	30.5	24.7	18.2	19.7	22.7	22.1
5.0 - 5.9	19.0	19.4	20.8	20.2	15.5	8.3	7.8	10.6	9.0	18.3	19.3	19.4
6.0 - 6.9	13.0	12.7	11.2	9.1	4.1	3.3	3.3	3.6	6.1	10.9	13.4	12.3
7.0 - 7.9	9.6	9.0	7.2	5.2	2.6	2.7	2.1	3.4	6.1	7.0	7.8	9.9
8.0 - 8.9	8.3	8.6	5.6	4.5	6.0	6.4	5.5	7.3	8.8	6.9	6.5	7.6
9.0 - 9.9	5.4	5.8	5.2	4.9	8.7	12.4	11.1	10.2	8.9	7.5	5.2	4.8
10.0 - 10.9	5.7	5.0	3.8	4.8	4.9	4.3	3.0	3.9	7.5	5.6	5.2	3.7
11.0 - 11.9	4.3	4.1	5.0	4.1	4.4	1.4	0.3	1.9	5.2	4.7	3.6	3.7
> 12.0	3.2	4.7	7.5	6.5	4.3	0.9	0.8	3.0	8.3	7.5	6.5	6.6

Additional wave information was obtained from the Coastal Hazard System (CHS) (CHL 2021) which was created as part of the South Atlantic Coastal Study (SACS). CHS is a statistical and probabilistic framework for comprehensive characterization of storm climatology. The CHS includes high-resolution numerical modeling that produces wave heights and still-water levels for storms with annual exceedance probabilities between two years and 10,000 years. The CHS modeled three sea level change scenarios. SLC0 includes 0 feet of sea level rise (current conditions), SLC1 includes 2.73 feet of sea level rise, and SLC2 includes 7.35 feet of sea level rise. These values correspond to approximately years 2077 for SLC1 and 2127 for SLC2 under the USACE high curve. Table A-6 and Table A-7 display the average significant wave height outputs (based on the average values at three CHS output Save Points) for the Main Segment and Key Biscayne Segment of the Miami-Dade County shoreline for the ocean-facing shoreline and back bay shorelines, respectively.

Table A-6. Average CHS Significant Wave Height Outputs for the Ocean-Facing Shoreline of Miami-Dade County

Project Segment	Scenario	Annual Exceedance Probability (1 in x) [Hm0 in ft]								
		2	5	10	20	50	100	200	500	1000
Main Segment[1]	SLC0	5.77	7.49	8.23	8.70	9.11	9.35	9.57	9.89	10.14
Main Segment[1]	SLC1	6.31	8.42	9.31	9.85	10.32	10.60	10.86	11.20	11.49
Main Segment[1]	SLC2	6.76	9.74	11.11	11.91	12.60	13.00	13.36	13.90	14.42
Key Biscayne[2]	SLC0	2.10	2.78	3.14	3.37	3.62	3.84	4.07	4.31	4.45
Key Biscayne[2]	SLC1	4.14	4.85	5.11	5.25	5.37	5.56	5.74	5.93	6.05
Key Biscayne[2]	SLC2	6.03	7.18	7.53	7.74	7.97	8.18	8.36	8.57	8.72

[1]Averaged from CHS Output Save Points 31637, 31983, and 32134
[2]Averaged from CHS Output Save Points 32453, 32484, and 32534

Table A-7. Average CHS Significant Wave Height Outputs for Back Bay Shoreline of Miami-Dade County

Project Segment	Scenario	Annual Exceedance Probability (1 in x) [Hm0 in ft]								
		2	5	10	20	50	100	200	500	1000
Main Segment[1]	SLC0	0.82	1.11	1.46	1.75	2.05	2.22	2.34	2.51	2.62
Main Segment[1]	SLC1	0.97	1.36	1.79	2.13	2.51	2.75	2.92	3.09	3.22
Main Segment[1]	SLC2	1.30	1.75	2.15	2.59	3.11	3.45	3.70	3.97	4.13
Key Biscayne[2]	SLC0	1.92	2.44	2.71	3.06	3.43	3.67	3.89	4.16	4.30
Key Biscayne[2]	SLC1	2.43	3.04	3.32	3.65	4.06	4.31	4.52	4.80	4.98
Key Biscayne[2]	SLC2	3.04	3.86	4.25	4.71	5.23	5.53	5.78	6.12	6.37

[1]Averaged from CHS Output Save Points 31711, 31845, and 32057
[2]Averaged from CHS Output Save Points 32475, 32500, and 32538

4.3 TIDES

The gravitational pull of the moon and sun create astronomical tides which are predictable in magnitude and timing. The National Oceanic and Atmospheric Administration (NOAA) regularly publishes tide tables for selected locations along the coastlines of the Unites States and around the world. These tables provide times of high and low tides as well as predicted tidal amplitudes.

Tidal datums for the Main Segment were obtained from NOAA tide stations 8723080 Haulover Pier which is just north of Bakers Haulover Inlet and 8723170 Miami Beach near the southern terminus of the Main Segment. For Key Biscayne, tidal datums were obtained from NOAA tide station 8723214 Virginia Key which is north of the Key Biscayne study area. Table A-8 summarizes the tidal datums. The tide range (the difference between Mean High Water and Mean Low Water) is 2.47 feet at the north end of the Main Segment, 2.46 feet at the southern end of the Main Segment, and 2.03 feet near Key Biscayne.

Table A-8. Tidal Datums

Tidal Datum	Elevation (feet) Relative to NAVD88		
	Station 8723080 (Haulover Pier)	Station 8723170 (Miami Beach)	Station 8723214 (Virginia Key)
Mean Higher High Water (MHHW)	0.43	0.33	0.23
Mean High Water (MHW)	0.36	0.25	0.15
North American Vertical Datum (NAVD88)	0.00	0.00	0.00
Mean Sea Level (MSL)	-0.86	-0.96	-0.89
Mean Low Water (MLW)	-2.11	-2.21	-1.88
Mean Lower Low Water (MLLW)	-2.25	-2.37	-2.02

4.4 STORM EFFECTS

Tropical systems influence the shoreline of Miami-Dade County during the summer and early fall, and Nor'easters influence the shoreline during the late fall into the early spring. Nor'easter events are frequent throughout the winter, whereas tropical events are more sporadic. Although hurricanes typically generate larger waves and storm surge, winter storms may have a greater impact on the shoreline because of their longer duration and higher frequency.

During intense storm activity, the shoreline is expected to naturally modify its beach profile. Storms erode and transport sediment from the beach into the active zone of storm waves. Once caught in the waves, this sediment is carried along the shore and redeposited farther down the beach or is carried offshore and stored temporarily in submerged sand bars. Periodic and unpredictable hurricanes and coastal storms, with their intense breaking waves and elevated water levels, can change the width and elevation of beaches and accelerate erosion. After storms pass, gentle waves usually return sediment from the sand bars to the beach, which is restored gradually to its natural shape. While the beach profile typically recovers from storm energy as described, extreme storm events may cause sediment to leave the beach system entirely, sweeping it into inlets or far offshore into deep water where waves cannot return it to the beach. Therefore, a portion of shoreline recession due to intense storms may never fully recover.

Miami-Dade County is in an area of significant storm activity. Figure A-10 shows historic tracks of hurricanes and tropical storms from 1842 to 2020 as recorded by the National Hurricane Center (NHC). These hurricane data are available from the NOAA at https://coast.noaa.gov/hurricanes/#map=4/32/-80. The dotted circle in the center of this figure indicates a 50-nautical-mile radius drawn from the center of the study area. Based on NHC records, 90 tropical storms, hurricanes, and extratropical storms have passed within this 50-mile radius over the 178-year period of record. The 50-mile radius was chosen for display purposes in Figure A-10 because any tropical disturbance passing within this distance, even a weak tropical storm, would be likely to produce some damage along the shoreline. Stronger storms can produce significant damage to the coastline from far greater distances.

Since the initial construction of the Main Segment of the authorized project in 1975, 17 named storms have passed within the 50-mile radius. These include notable storms such as Hurricane Andrew in 1992 and Hurricanes Katrina and Wilma in 2005. Damages from these storms within 50 miles, as well as from more distant storms causing indirect impacts, included substantial erosion and damage from winds, waves, and elevated water levels.

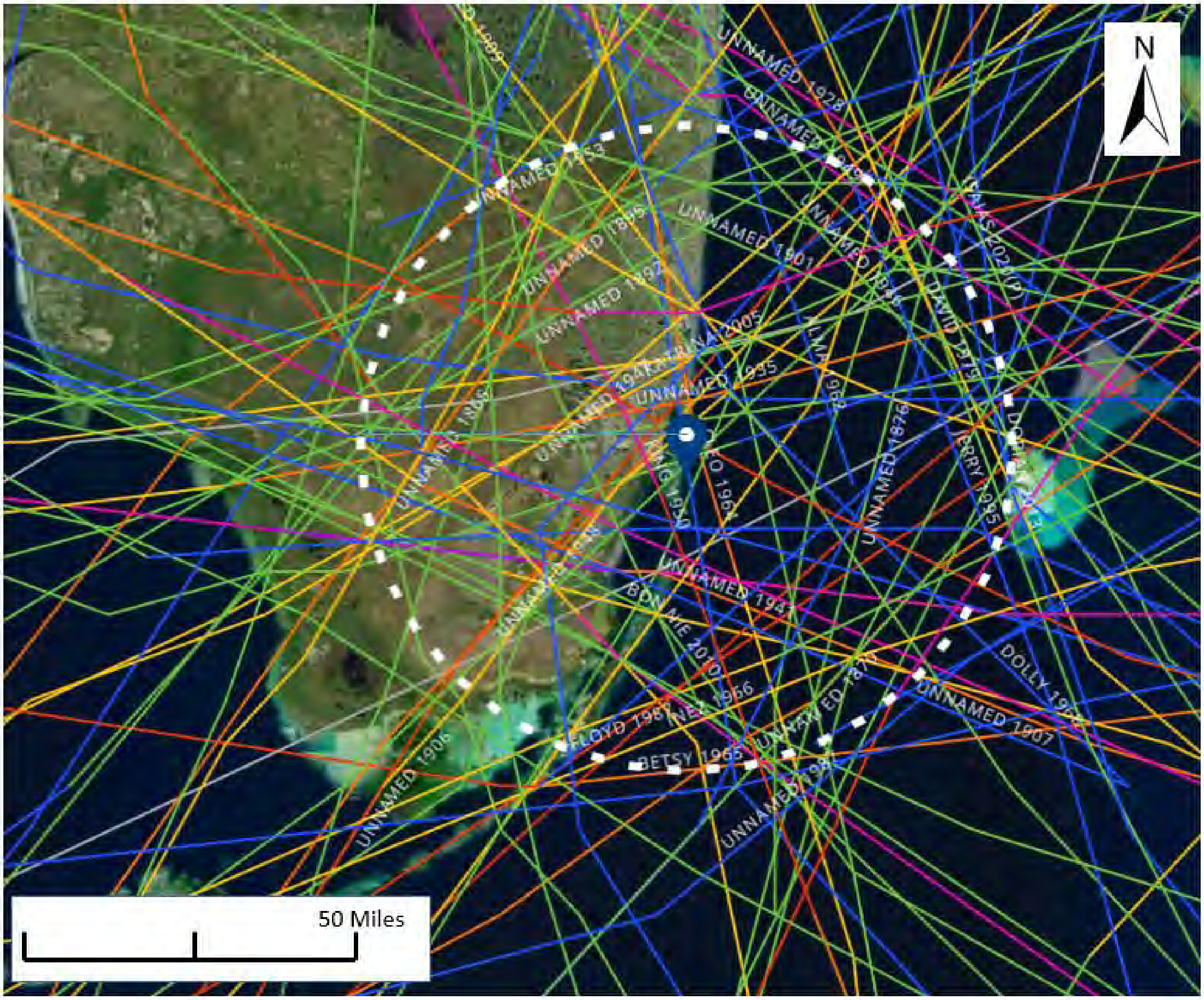


Figure A-10. Historic Storm Tracks - Hurricanes and Tropical Storms (1842 - 2020, 50-Mile Radius)

4.5 STORM SURGE

Storm surge is defined as the rise of the ocean surface above its astronomical tide level due to storm forces. Surges occur primarily because of atmospheric pressure gradients and surface stresses created by wind blowing over a water surface. Strong onshore winds pile up water near the shoreline, resulting in super-elevated water levels along the coastal region and inland waterways. In addition, the lower atmospheric pressure which accompanies storms also contributes to a rise in water surface elevation. Extremely high wind velocities coupled with low barometric pressures (such as those experienced in tropical storms, hurricanes, and very strong Nor'easters) can produce very high, damaging water levels. In addition to wind speed, direction, and duration, storm surge is also influenced by water depth, length of fetch (distance over water), and frictional characteristics of the nearshore sea bottom. An estimate of storm surge is required for the design of beach fill crest elevations. An increase in water depth may increase the potential for coastal flooding and allow larger storm waves to attack the shore.

The dune system along the Main Segment of the study area has an average elevation range of approximately 10 to 11 feet NAVD88 (with some spots as low as 9 ft and as high as 16 ft NAVD88). The authorized dune height for the expiring BEC&HP project is 11.2 feet NAVD88. The elevation of the existing dunes in Key Biscayne is approximately 8 feet NAVD88. These dunes act as a protective barrier against the effects of overtopping from extreme storm surges. The authorized dune height for the Main Segment is at a higher elevation than the storm surge elevations under current conditions and sea level change conditions expected within the project lifetime (see Section 4.6); however, the existing dunes in Key Biscayne are susceptible to overtopping from extreme storm surges. This can be seen from Table A-9 which provides ocean still water elevations versus storm frequency for several R-Monument locations along the Main Segment and Key Biscayne, taken from the Federal Emergency Management Agency (FEMA) Flood Insurance Study (FIS) conducted in 2009 (FEMA 2009. The stillwater elevations presented include the effects of astronomical high tide, storm surge (wind and pressure setup), and wave setup.

Table A-9. Storm Surge Elevations

Return Period (Years)	Total Still Water Elevations (feet, NAVD88)										
	R-30	R-34	R-38	R-45	R-51	R-56	R-67	R-94	R-101	R-106	R-113
10	3.6	3.6	3.6	3.7	3.8	3.8	3.8	4.4	4.0	4.0	4.1
50	4.8	4.8	4.8	4.9	5.0	5.1	5.1	5.7	5.3	5.3	5.4
100	5.2	5.3	5.3	5.4	5.5	5.6	5.5	6.2	5.7	5.7	5.8
500	6.1	6.2	6.2	6.3	6.5	6.5	6.5	7.2	6.8	6.8	6.9

Additional water elevation information was obtained from the CHS. As described in Section 4.2: Waves, the CHS provides statistical information of coastal hazards under current and future sea level conditions. Table A-10 and Table A-11 display the average still water elevation outputs for the Main Segment and Key Biscayne Segment of the Miami-Dade County shoreline for the ocean-facing shoreline and back bay shorelines, respectively.

Table A-10. Average CHS Stillwater Elevations for Ocean-Facing Shoreline of Miami-Dade County

Project Segment	Scenario	Annual Exceedance Probability (1 in x) [SWL in ft, NAVD88]								
		2	5	10	20	50	100	200	500	1000
Main Segment[1]	SLC0	2.73	3.23	3.59	4.04	4.71	5.21	5.66	6.17	6.50
Main Segment[1]	SLC1	5.45	5.93	6.25	6.66	7.29	7.76	8.20	8.70	9.02
Main Segment[1]	SLC2	10.05	10.50	10.78	11.12	11.66	12.10	12.51	12.98	13.28
Key Biscayne[2]	SLC0	2.83	3.49	4.16	4.87	5.78	6.45	6.97	7.51	7.85
Key Biscayne[2]	SLC1	5.51	6.10	6.68	7.35	8.22	8.87	9.39	9.93	10.29
Key Biscayne[2]	SLC2	10.06	10.58	11.01	11.56	12.37	13.01	13.52	14.05	14.41

[1]Averaged from CHS Output Save Points 31637, 31983, and 32134
[2]Averaged from CHS Output Save Points 32453, 32484, and 32534

Table A-11. Average CHS Stillwater Elevations for Back Bay Shoreline of Miami-Dade County

Project Segment	Scenario	Annual Exceedance Probability (1 in x) [SWL in ft, NAVD88]								
		2	5	10	20	50	100	200	500	1000
Main Segment[1]	SLC0	2.80	3.37	3.93	4.45	5.00	5.40	5.80	6.25	6.55
Main Segment[1]	SLC1	5.51	6.03	6.53	7.00	7.52	7.91	8.30	8.75	9.08
Main Segment[1]	SLC2	10.15	10.70	11.20	11.70	12.32	12.75	13.13	13.57	13.89
Key Biscayne[2]	SLC0	2.80	3.52	4.37	5.33	6.55	7.26	7.81	8.41	8.79
Key Biscayne[2]	SLC1	5.49	6.12	6.85	7.72	8.88	9.56	10.11	10.72	11.11
Key Biscayne[2]	SLC2	10.06	10.60	11.17	11.91	12.94	13.57	14.08	14.65	15.02

[1]Averaged from CHS Output Save Points 31711, 31845, and 32057
[2]Averaged from CHS Output Save Points 32475, 32500, and 32538

4.6 SEA LEVEL RISE

4.6.1 RELATIVE SEA LEVEL RISE

Relative sea-level change (RSLC) was calculated using the USACE sea level change curve calculator which is available at: http://www.corpsclimate.us/ccaceslcurves.cfm. This calculator uses the methodology described in Engineer Regulation (ER) 1100-2-8162, Incorporating Sea Level Changes in Civil Works Programs (USACE 2019a) and Engineering Pamphlet (EP) 1100-2-1 (USACE 2019b).

Extreme water levels (EWL) incorporated into the calculator are based on statistical probabilities using recorded historic monthly extreme water level values. EWL analysis is described below. NOAA Technical Report NOS CO-OPS 067, Extreme Water Levels of the United States 1893-2010 describes the methods and data used in the calculation of the exceedance probability levels using a generalized extreme value statistical function (NOAA 2013). The USACE method uses the same NOAA recorded monthly extreme values in a percentile statistical function. Both methods use data recorded and validated by NOAA at the long-term, established tide gauges. The extreme values at the gauge can be significantly different than what may occur at the project site due to differences in site characteristics and complex interactions of physical forces that vary between the locations. The level of confidence in the exceedance probability decreases with longer return periods. Additional information is available at the Center for Operational Oceanographic Products and Services (CO-OPS) website at: https://tidesandcurrents.noaa.gov/.

Relative sea level (RSL) refers to local elevation of the sea with respect to land, including the lowering or rising of land through geologic processes such as subsidence and glacial rebound. It is anticipated that sea level will rise within the next 100 years. To incorporate the direct and indirect physical effects of projected future sea-level change on design, construction, operation, and maintenance of coastal projects, USACE has provided guidance in Engineer Circular (EC) 1165-2-212, Sea-Level Change Considerations for Civil Works Programs (USACE 2012) which has been superseded by ER 1100-2-8162, Sea-level Change Considerations in Civil Works Programs and EP 1100-2-1, Procedures to Evaluate Sea Level Change: Impacts, Response, and Adaption (USACE 2019a and 2019b).

ER 1100-2-8162 provides both a methodology and a procedure for determining a range of sea level change estimates based on global sea level change rates, the local historic sea level change rate, the construction (base) year of the project, and the design life of the project. Three estimates are required by the guidance, a Low (Baseline) estimate representing the minimum expected sea level change, an Intermediate estimate, and a High estimate representing the maximum expected sea level change.

These estimates are referenced to the midpoint of the latest National Tidal Datum epoch, 1992. The reader is referred to ER 1100-2-8162 for a detailed explanation of the procedure, equations employed, and variables included to account for the eustatic change as well as site-specific uplift or subsidence to develop corrected rates.

At the kickoff of the study, the Miami-Dade County Project Delivery Team (PDT), PDTs for the neighboring Monroe County and Miami-Dade Back-bay studies, and the USACE Climate, Preparedness, and Resilience Community of Practice (CPR COP) discussed the application of USACE guidance of RSLC in this area. Figure A-11 shows the locations of these three study areas and six long period tide gauges in South Florida, and Table A-12 shows the periods of record and relative sea-level trend at each of the gauges.

The gauge closest in proximity to Miami-Dade County is the Miami Beach gauge. Typically, this gauge and its associated record would be selected to guide the sea level change strategy for the feasibility study due to its proximity and long period of record. However, the gauge was discontinued in 1981, and the published sea-level trend does not reflect sea-level change over the past 40 years and any potential acceleration in sea level change. A new gauge within about three miles was subsequently established at Virginia Key in 1994; however, the large temporal gap and spatial differences in gauges makes combining these records prohibitive.

Of the other five gauges remaining in south Florida, the two on the Gulf of Mexico are screened out due to their location on the Gulf of Mexico and distance from the study areas. Of the three remaining gauges, the two in closest proximity to Miami-Dade County, Lake Worth Pier, and Vaca Key have very similar periods of record and similar sea level change trends of approximately 0.012 ft/yr (3.7 mm/yr) with a 95% confidence interval of +/- 0.0015 ft/yr (0.46 mm/yr) for Vaca Key and +/- 0.0019 ft/yr (0.58 mm/yr) for Lake Worth Pier. The Key West gauge has a much longer period of record and much lower sea-level change trend of 0.0079 ft/yr (2.42 mm/yr) with a 95% confidence interval of +/- 0.00049 ft/yr (0.15 mm/yr). Analysis of this gauge via the NOAA “Variation of 50-year trends” tool on the NOAA Tides and Currents website shows that changing the mid-point of a 50-year averaging period to an averaging period like Lake Worth Pier and Vaca Key can produce very different sea-level change trends as shown in Figure A-12. What is evident from the figure is that the sea-level change trend has been increasing with the highest level reported utilizing the most recent averaging period. This points to an increase in the sea level change trend throughout southeast Florida.

Figure A-11. Locations of Long-Period Tidal Records in South Florida along with County Boundaries

Table A-12. South Florida Tide Gauges, Periods of Record, and Relative Sea Level Trend

Tide Gauge	Station Number	Period of Record	Relative Sea Level Trend (ft/yr)	Relative Sea Level Trend (mm/yr)
Fort Myers	8725520	1965 - Present	0.010 ± 0.0016	3.10 ± 0.49
Naples	8725110	1965 - Present	0.009 ± 0.0015	2.80 ± 0.45
Key West	8724580	1913 - Present	0.008 ± 0.0005	2.42 ± 0.15
Vaca Key	8723970	1971 - Present	0.012 ± 0.0015	3.69 ± 0.46
Miami Beach	8723170	1931 - 1981	0.008 ± 0.0014	2.39 ± 0.43
Lake Worth Pier	8722670	1970 - Present	0.012 ± 0.0019	3.70 ± 0.58

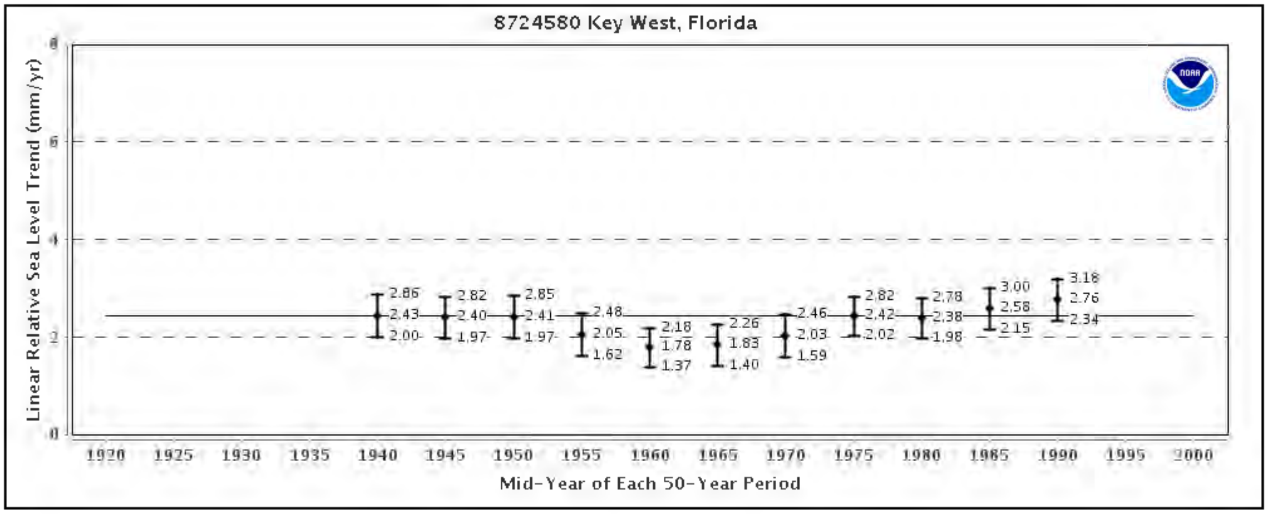


Figure A-12. Variation of 50-year Trends at the Key West Tide Gauge
(https://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?plot=50yr&id=8724580)

Vertical land movement data is available at both Miami and Key West from National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) (https://sideshow.jpl.nasa.gov/post/series.html). The land movement at both sites were examined (Figure A-13 and Figure A-14). The Miami site (MIA3) appears to reflect a distinct shift in horizontal location during the record which leads to a highly uncertain trend in vertical land movement of -0.0009 ± 0.0011 ft/yr (-0.276 ± -0.343 mm/yr). For Key West (KYW1), the vertical land movement trend is -0.0013 ± 0.0012 ft/yr (-0.398 ± -0.378 mm/yr). Due to the short record for both locations, there is tremendous uncertainty in both records. Nevertheless, both locations point to a slight decrease in land surface height over time. Both the Florida Keys and Miami are subject to similar large-scale oceanographic forcing. Due to their orientations, the predominant wave characteristics are different at each site, but the larger scale physical oceanography is similar. Figure A-15 shows a “spaghetti plot” of the trajectories of all NOAA Atlantic Oceanographic Meteorological Laboratory (AOML) Drifting Buoy Data Assembly Center’s archived near-surface buoys from 1978 to 2003. The corresponding speeds of the trajectories are color-coded which makes the major currents visible. It is evident in the plot that the gauges located in the Keys and those off the Southeast Florida mainland coast are both predominantly subject to the Florida current.

Based on the increase in sea-level change trend observed in Key West, and the similarity in sea-level change trend for both Vaca Key and Lake Worth Pier along with similar vertical land movement and physical oceanographic conditions throughout the area, it is appropriate to use the sea-level change rate at Vaca Key or Lake Worth Pier for the Miami-Dade and Monroe County studies. With Vaca Key located within Monroe County and within similar proximity to the focus areas of the Miami-Dade studies as Lake Worth Pier, the Vaca Key tide gauge and associated sea-level change trend was adopted for both the Monroe and Miami-Dade County feasibility studies.

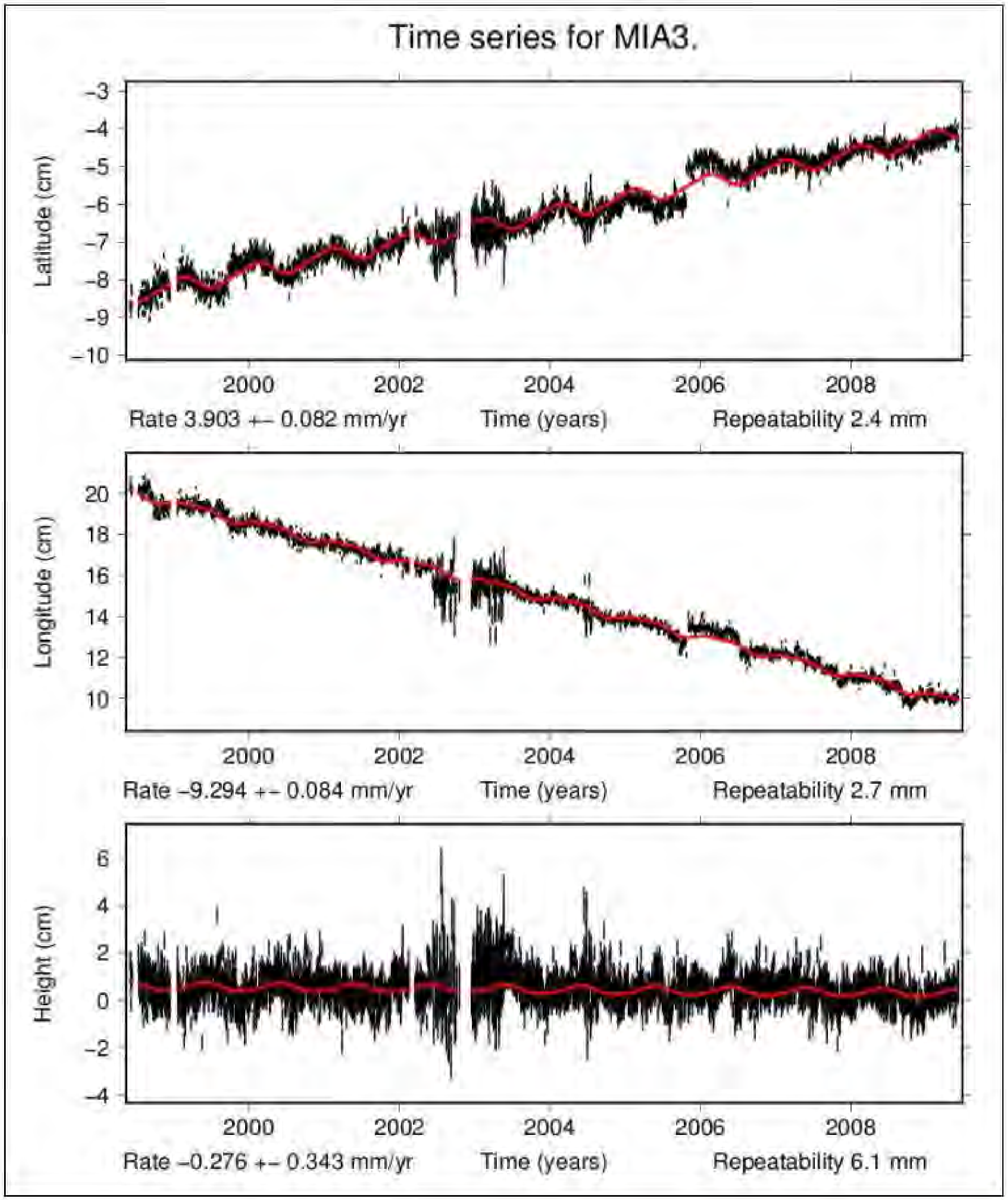


Figure A-13. Land Movement at Miami (https://sideshow.jpl.nasa.gov/post/links/MIA3.html)

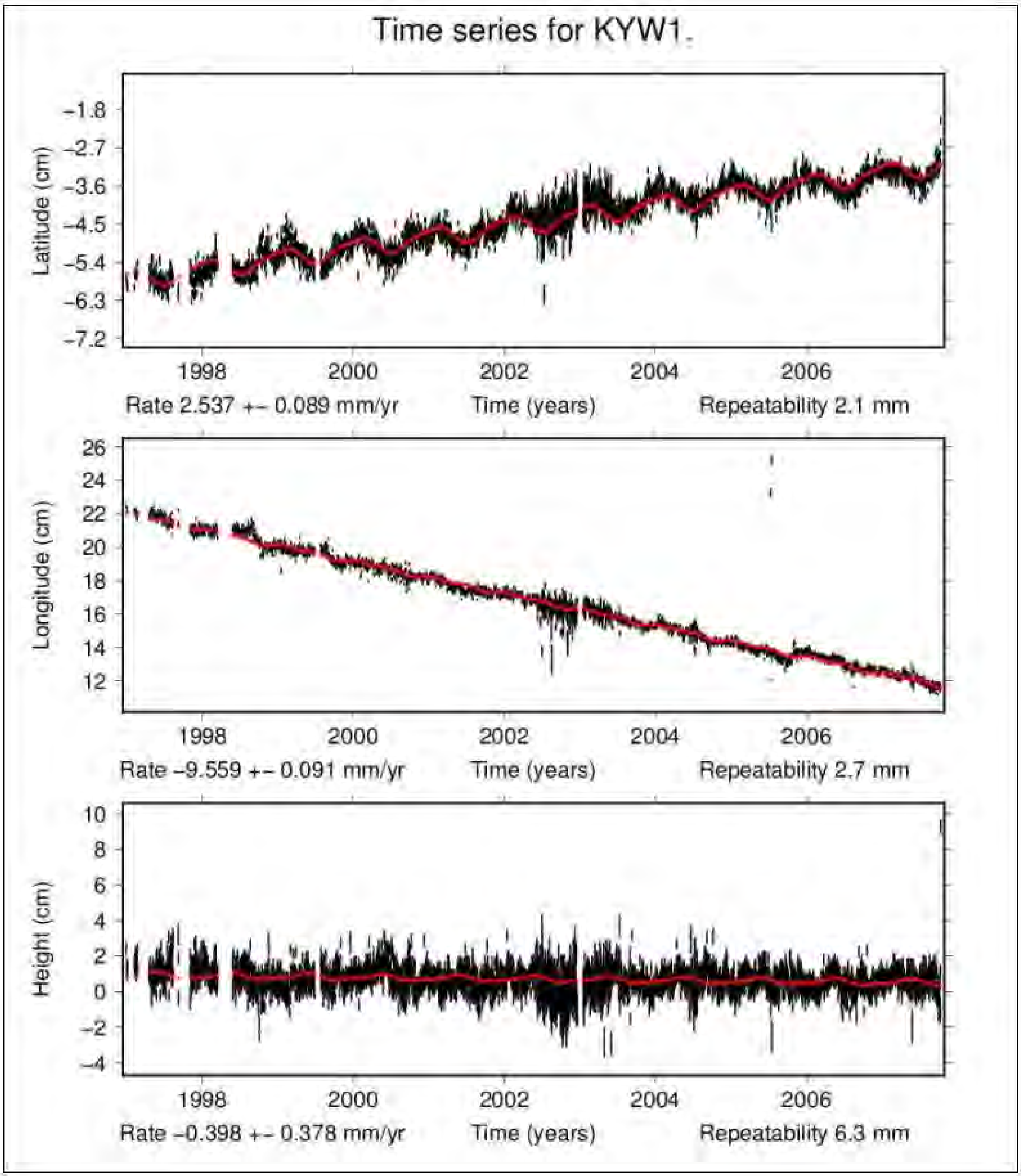


Figure A-14. Land Movement at Key West
(https://sideshow.jpl.nasa.gov/post/links/KYW1.html)

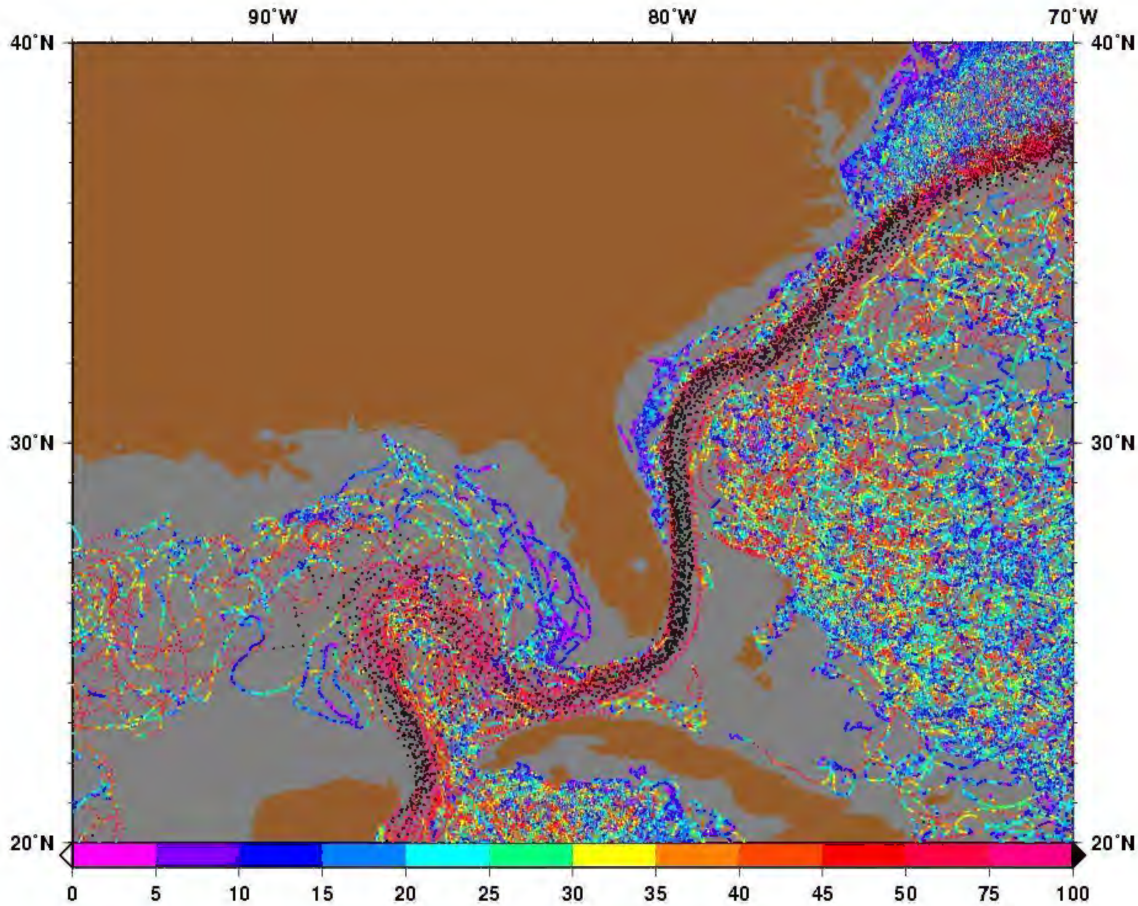


Figure A-15. Spaghetti Plot of the Trajectories of all NOAA AOML Drifting Buoy Data Assembly Center's Archived Near-surface Buoys from 1978 to 2003. The Corresponding Speeds of the Trajectories are Color-coded which Makes the Major Currents Visible.
(https://oceancurrents.rsmas.miami.edu/caribbean/spaghetti-speed/florida.jpg)

Based on historical sea-level measurements taken from National Ocean Service (NOS) gage 8723970 at Vaca Key, Florida, the historic sea-level change rate was determined from the USACE sea-level change curve calculator (https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html). The economic analysis period for this study begins with a Beach-*fx* model start date of 2025 (economic base year of 2026) and extends to the end of the project life at the end of 2075. The USACE calculator gives an SLC rate of 0.0091 ft/yr (2.78 mm/yr) based on NOAA's 2006 published rate. However, NOAA currently reports that the mean sea-level trend is 0.0128 ft/yr (3.91 mm/yr) with a 95% confidence interval of +/- 0.0014 ft/yr (0.44 mm/yr) based on monthly mean sea-level data over a continuous 49-year record (1971 to 2020) (https://tidesandcurrents.noaa.gov/sltrends/; Figure A-16). Therefore, SLC curves and extreme water-level data generated using the USACE sea-level change curve calculator are likely to under predict when compared with the latest information presented by NOAA.

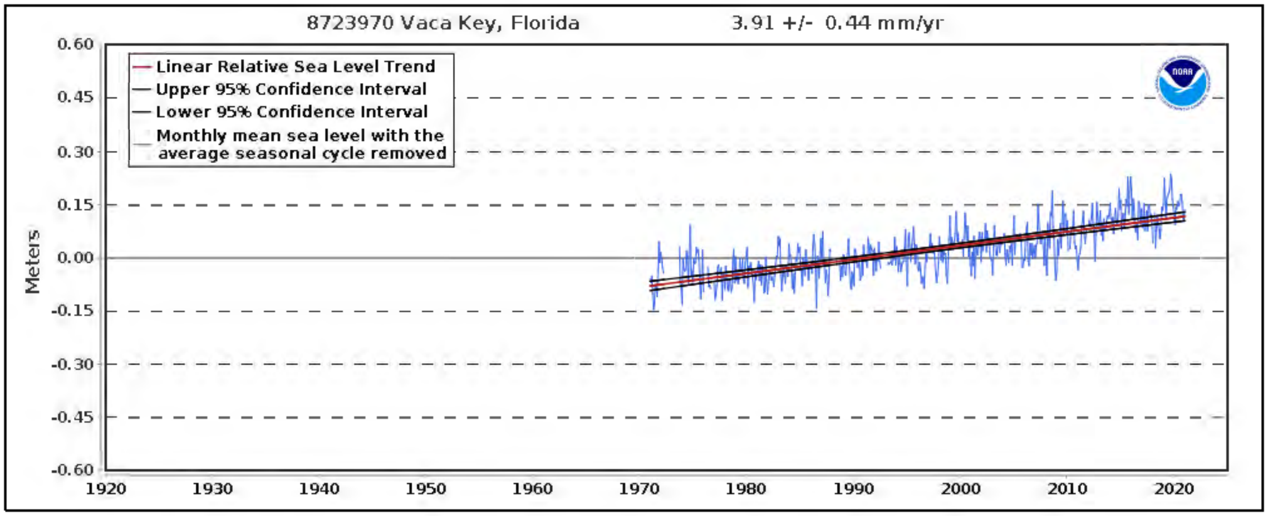


Figure A-16. Relative Sea-Level Trend, NOAA Gauge 8723970 (1979 to 2019)

Applying the USACE SLC curve calculator, the 2.78 mm/yr rate is equivalent to a change of 0.76 feet between 1992 and 2075, or a change of 0.46 feet over the life of the project, beginning in the project start year (2026 to 2075). The USACE Intermediate and High curves are non-linear; therefore, the rate of change is variable with time and were determined to range from 4.6 mm/year (0.015 feet/year) to 6.0 mm/year (0.020 feet/year) and from 10.6 mm/year (0.035 feet/year) to 16.1 mm/year (0.052 feet/year), respectively (Figure A-17). Over the 50 years from 2026 to 2075 the average rate of change for the Intermediate curve is 3.96 mm/year (0.013 feet/year) and the USACE High rate was determined to be 16.09 mm/year (0.053 feet/year). These rates result in an Intermediate and High change in sea level between the project start year (2026) and the end of the project's life (2075) of 0.98 feet and 2.64 feet, respectively. Figure A-18 shows RSLC from 1992 and 2080 for all three USACE curves. The USACE High curve was chosen to represent sea-level rise for this study as it is the USACE curve that best represents the sea-level change in the project area.

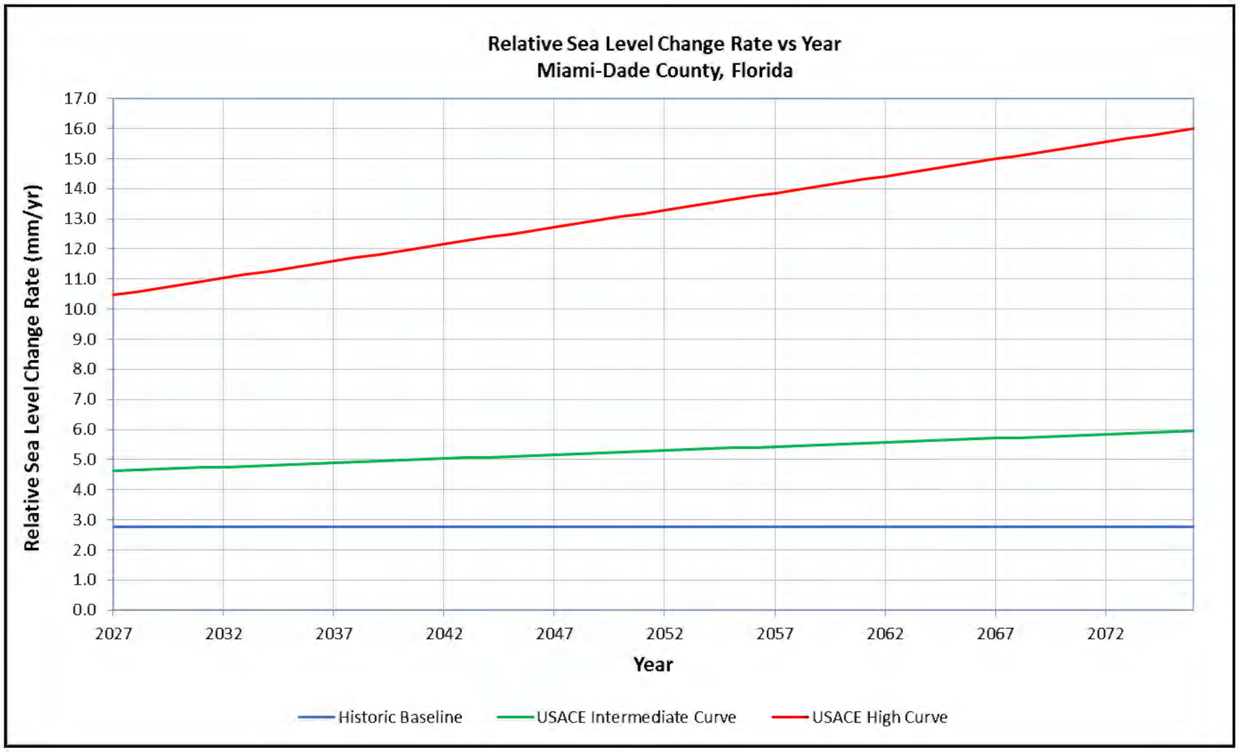


Figure A-17. Relative Sea-Level Change Rates over the Life of the Project

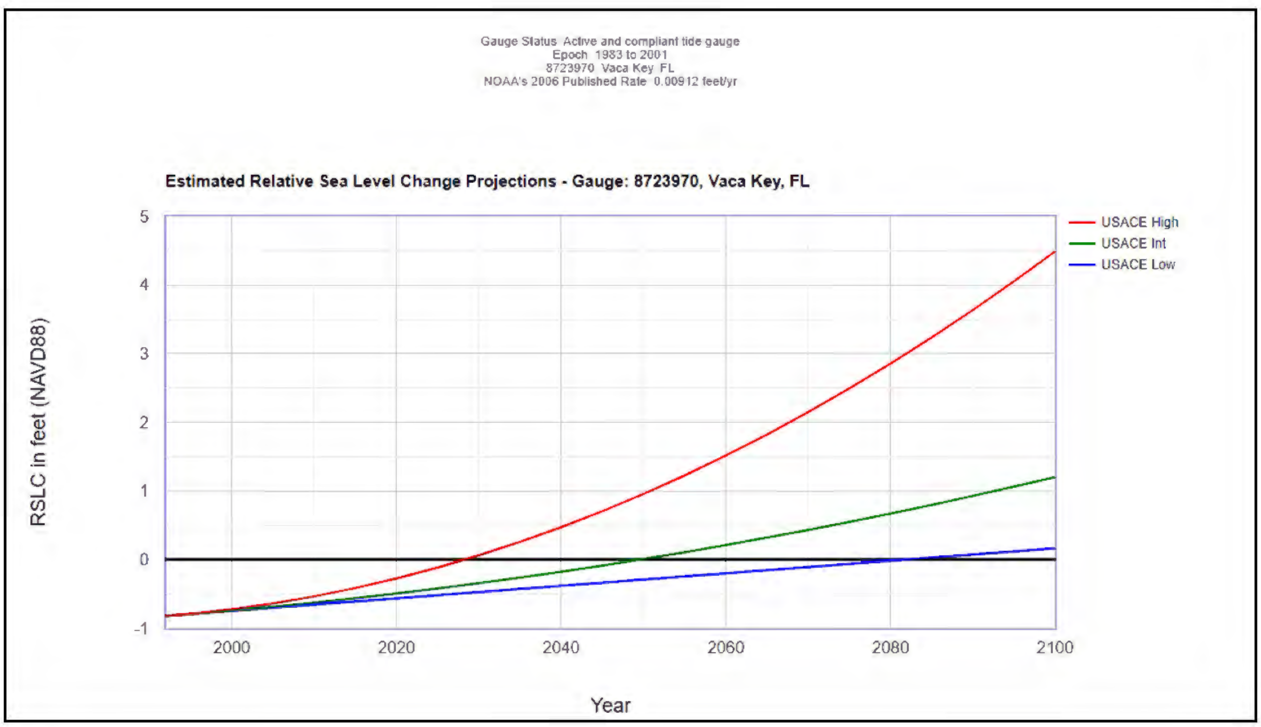


Figure A-18. USACE Project Sea-Level Change

4.7 STORM TIDE AND BACK BAY FLOODING

The FEMA Base Flood Elevation (BFE), defined as the 1% Annual Exceedance Probability (AEP) Flood, is the regulatory requirement for the elevation or floodproofing of structures and are referenced to FEMA panels (Figure A-19 and Figure A-20). BFE, along the ocean facing shoreline of the Main Segment, is approximately 11.0 ft NAVD88 (~10.1 ft-MSL) for the entire segment absent of the far southern segment where it drops to 9.0 ft-NAVD88 (~8.1 ft-MSL). The BFE for the ocean-facing shoreline of Key Biscayne is also 11.0 ft NAVD88 (~10.1 ft-MSL). The back bay shoreline of Main Segment has a BFE of approximately 7.0 to 8.0 ft NAVD88 (~6.1 to 7.1 ft MSL) while the back bay shoreline of Key Biscayne has a BFE of 9 to 10.0 ft NAVD88 (~8.1 to ~9.1 ft-MSL). The BFEs on the ocean-facing shorelines for both the Main Segment and Key Biscayne include the effects of wave-induced flooding while the BFEs for the back bay shorelines do not. The BFE is used in this study to help analyze the expected flooding elevations for the 1% AEP flood in the study area. Using the SLC calculator, the BFE was plotted relative to relative sea-level change for the Main Segment (Figure A-21). Tidal datums and extreme water levels (including the BFE) are shown in Figure A-22. The definition of each tidal datum acronym can be found at the NOAA Tides and Currents website (https://tidesandcurrents.noaa.gov/datum_options.html).

Table A-13 shows a comparison of the 1% AEP water elevations evaluated during this study. The water elevations in the table are for current sea level conditions and are expected to rise with SLC. These water elevations are used to verify the Beach-*fx* model output water levels for accuracy and evaluate the level of protection provided by the CSRM measures. As discussed in Section 6.2, none of these values are used as input for the modelling. Instead, a recently updated FEMA suite of storms was used in CSHORE to develop the Pre- and post-storm profiles, wave data, and water levels. This information was then imported into Beach-*fx*.

Table A-13: Comparison of Water Levels

Water Level	Parameters Included	1% AEP Water Elevations (ft-NAVD88)
FEMA SWL	1. Astronomical tides 2. Storm surge 3. Wave setup	5.2 – 6.2
CHS SWL	1. Astronomical tides 2. Storm surge 3. Wave setup	5.21 (Ocean-facing Main Segment) 6.45 (Ocean-facing Key Biscayne) 5.40 (Back bay Main Segment) 7.26 (Back bay Key Biscayne)
FEMA BFE	1. Astronomical tides 2. Storm surge 3. Wave setup 4. Wave runup	11 (Ocean-facing Main Segment) 11 (Ocean-facing Key Biscayne) 7 – 8 (Back bay Main Segment) 9 – 10 (Back bay Key Biscayne)

Potential impacts of rising sea level on total water levels experienced at the site include overtopping of waterside structures, increased shoreline erosion, and flooding of low-lying areas. Cross-sections were drawn along the Main Segment and Key Biscayne project areas at each model reach to determine the range of elevations across the barrier island. Elevations were plotted with the 1% (100 year) as well as the 10% (10 Year), 2% (50 Year), and 0.2% (500 Year) FEMA SWL AEP water elevations. Transect locations and corresponding cross-sections are shown in Attachment 1. These figures indicate that the Main Segment and Key Biscayne Segment are susceptible to widespread flooding from the back bay during a 2% AEP (50 Year) flood event with near total inundation at the 0.2% AEP (500 Year) flood elevation. At the end of Federal participation in 2075, the areas are susceptible to widespread flooding during a 10% AEP (10 Year) flood event with near total inundation at the 2% AEP (50 Year) flood elevation.

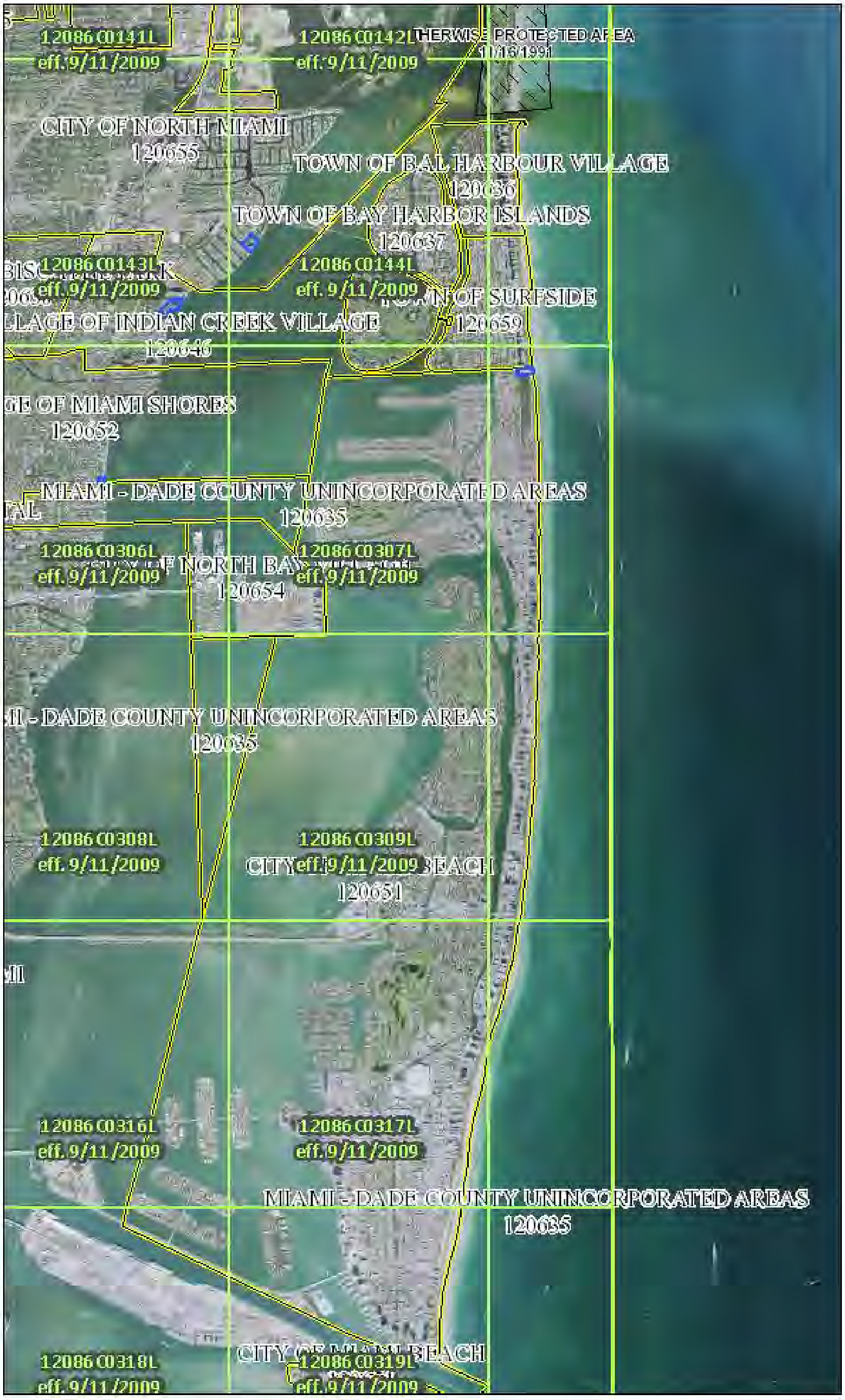


Figure A-19. FEMA Flood Map Panels for the Main Segment
(https://hazards-fema.maps.arcgis.com/apps/webappviewer/index.html)

Figure A-20. FEMA Flood Map Panels for the Key Biscayne (https://hazards-fema.maps.arcgis.com/apps/webappviewer/index.html)

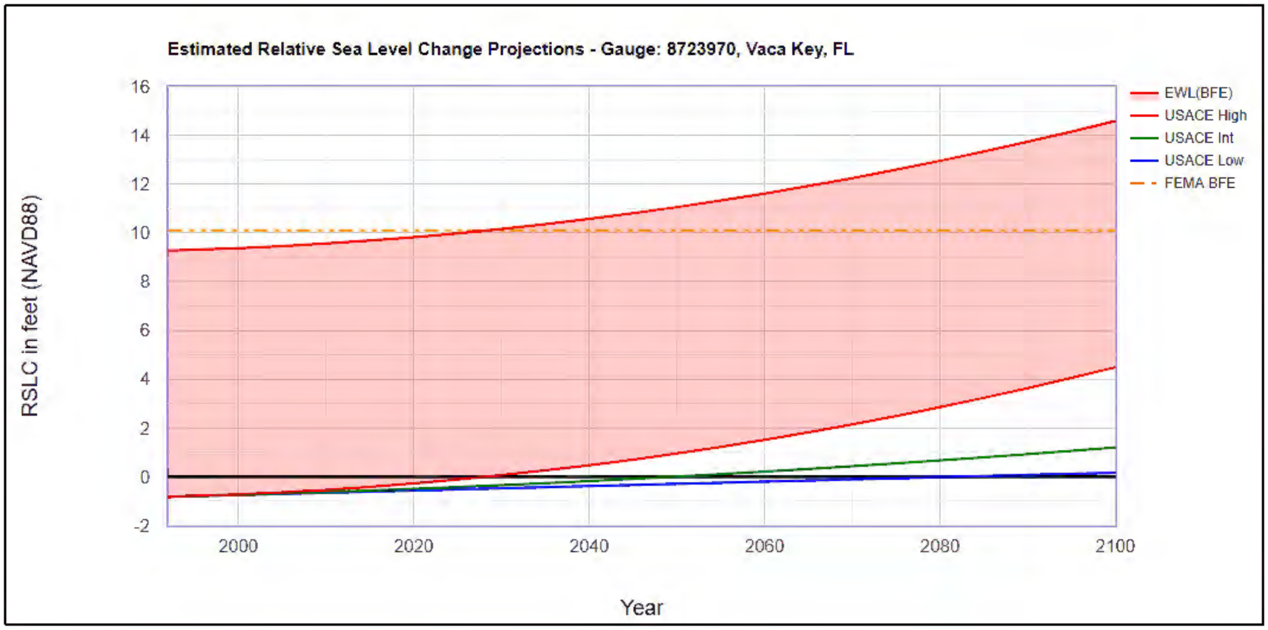


Figure A-21. Estimated Relative Sea-Level Change with Miami-Dade County BFE of 10.1 ft-MSL (https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html)

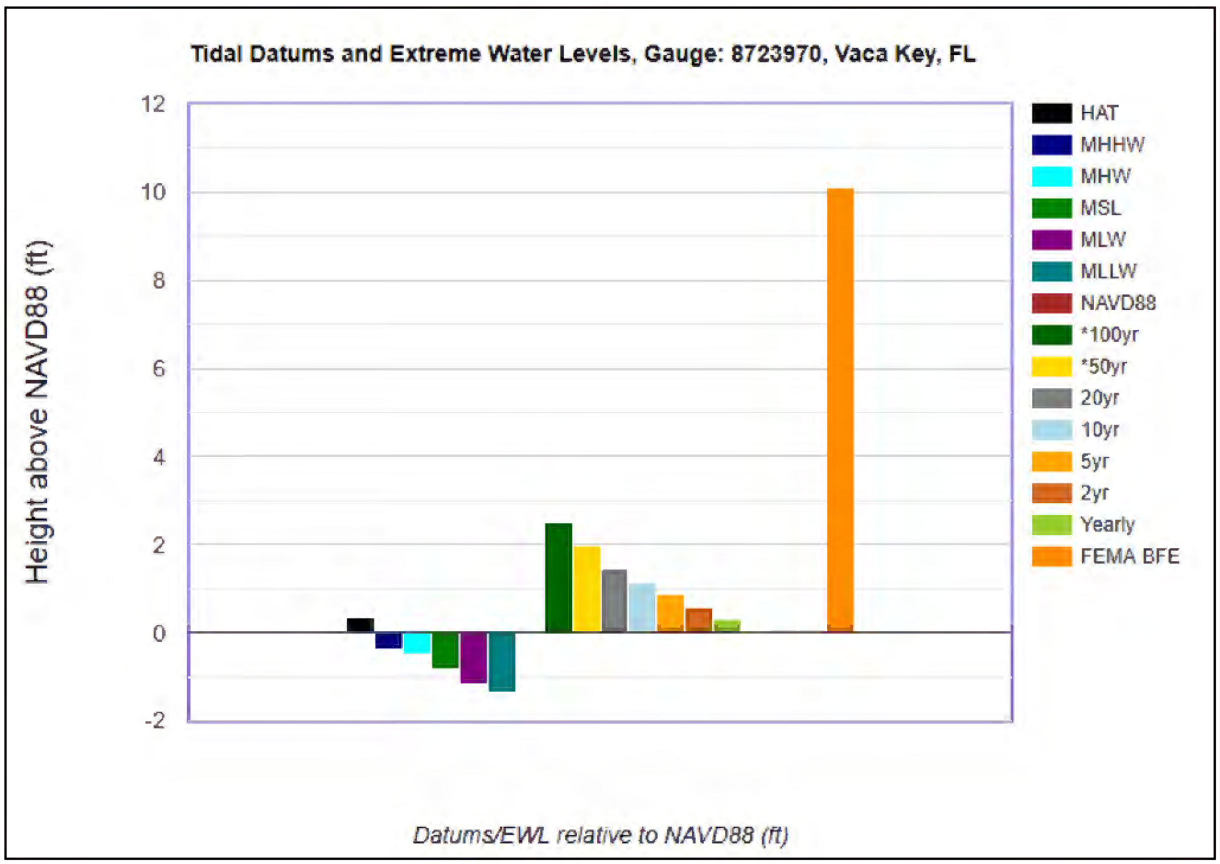


Figure A-22. Tidal Datums and Extreme Water Levels (https://cwbi-app.sec.usace.army.mil/rccslc/slcc_calc.html)

For the Main Segment, in general, RSLC (Baseline, Intermediate, and High) will not affect the overall function of the project as these elevations are far below that of the existing dune system. Relative vulnerability to flooding during extreme events is consistent between both with and without project conditions. However, low elevation on the interior barrier island makes it extremely vulnerable to back bay flooding. Therefore, the primary protection offered by the existing (and possible future) renourishment project is against erosion and wave damages.

The Key Biscayne Segment will be affected by RSLC because the dunes in this Segment (8-9 feet NAVD88) are lower than those typically existing in the Main Segment (10-11 feet NAVD88). The USACE High curve will cause 100-year storm surges to overtop the height of the dunes in many places by the end of the project's life based on the CHS return period values in scenario SLC1 (2.73 ft of sea level rise). Therefore, the primary protection offered by the existing (and possible future) renourishment project is against inundation originating from the ocean. The non-Federal sponsor is prepared to solve back bay flooding problems and associated risks.

Increasing sea levels will increase the back bay vulnerability making it more likely that any oceanside renourishment will need to be combined with more comprehensive flood management measures than to be implemented as a standalone project for complete protection of the barrier islands. The Miami-Dade back bay vulnerabilities are assessed in greater detail in the Miami-Dade Back Bay Coastal Storm Risk Management Study.

4.8 EXISTING SHORELINE ARMOR

Historically, the threat that shoreline erosion has posed to infrastructure has resulted in coastal armoring throughout a portion of the Main Segment and Key Biscayne. For more information on the distribution of armor see Appendix B: Economics.

5 EFFECTS OF ADJACENT FEATURES

5.1 INLET EFFECTS

The Main Segment is significantly influenced by inlets adjacent to the project area. Bakers Haulover inlet lies immediately to the north of the Main Segment. The Bal Harbour shoreline, which is just south the inlet, is a recognized erosional area. As shown in Figure A-2 and

Figure A-3., this area has been nourished frequently with many smaller nourishments featuring disposal of maintenance dredging material from the nearby Atlantic Intracoastal Waterway. On the southern end of the Main Segment is Government Cut which is the inlet to Miami Harbor. This area was identified as a sediment sink for the early lifetime of the original authorization.

However, in 1999 the north jetty of the inlet was rehabilitated and sand tightened (FDEP 2018). Since that time no additional nourishment of the area has occurred, and the area has been accretional and even used as a borrow source for nourishments in updrift portions of the segment.

Tidal currents associated with the inlets impact littoral transport of sediment at the northern and southern tips of the island. A detailed description of Bakers Haulover Inlet, including dredge histories and sediment budgets for adjacent beaches, are provided in the inlet management plans (CPE 1995 & Moffatt and Nichol 2019). There is not an inlet management plan for Government Cut; however, Water & Air (2018) provides details of the hydrodynamics in this area.

The Key Biscayne Segment is not affected by any adjacent inlets. The portion of Key Biscayne is in the central part of the barrier island with the north end of the island 2.1 miles away and the south end of the island 1.2 miles away.

5.2 STRUCTURE EFFECTS

The local sponsor built three attached rubble-mound breakwaters at 32nd Street in the Main Segment in 2002 to stabilize an existing erosion hotspot at R-59. These structures were effective at stabilizing the shoreline and alleviating the existing erosional hotspot but created a new hotspot to the south of the structures (R-60 to R-61) due to a sediment flux deficit. The existing structures trap material and prevent longshore sediment transport from the north creating a downdrift sand deficit. Material can flow around the structures in an offshore sandbar, but this sandbar only reattaches itself to the beach near R-63. This creates a 2,000-to-3,000-foot stretch of shoreline with a sediment influx deficiency.

Throughout the Main Segment there are numerous relic groins from before the BEC & HP Project. These groins are decrepit and no longer functioning. In most cases, the groins have remained buried or have been removed. The groins in Bal Harbour are sometimes exposed but none of these structures has any impact on the littoral drift for the project area. Details on the construction and composition of these structures is not available.

In Key Biscayne, a terminal groin structure was constructed at R-113.7 as part of the Federally authorized Key Biscayne Shore Protection Project (1985) in 1987. This structure is located 1.2 miles south of the area being evaluated in this report and does not have any direct impacts on the project area.

6 BEACH-*FX* LIFE-CYCLE SHORE PROTECTION PROJECT EVOLUTION MODEL

Federal participation in CSRM projects is based on a favorable economic justification in which the benefits of the project outweigh the costs. Determining the benefit to cost ratio (BCR) requires both engineering (project performance and evolution) and planning (alternative analysis and economic justification) analyses. The interdependence of these functions has led to the development of the life-cycle simulation model Beach-*fx*. Beach-*fx* combines the evaluation of physical performance and economic benefits and the costs of shore protection projects (Gravens et. al. 2007), particularly beach nourishment, to form the basis for determining the justification for Federal participation. This section describes the engineering aspects of the Beach-*fx* model. Because Key Biscayne was not initially scoped and was added after much of the Main Segment work was complete, many of the assumptions made for the Main Segment were carried into Key Biscayne for consistency.

6.1 BACKGROUND AND THEORY

Beach-*fx* is an event-driven life-cycle model. USACE guidance (USACE 2019c) requires that flood damage reduction studies include risk and uncertainty. The Beach-*fx* model satisfies this requirement by fully incorporating risk and uncertainty throughout the modeling process (input, methodologies, and output). Over the project life cycle, typically 50 years, the model estimates shoreline response to a series of historically based and synthetic storm events. These plausible storms, the driving events, are randomly generated using a Monte Carlo simulation, which is a simulation used to predict the probability of different outcomes with random variables. The corresponding shoreline evolution includes not only erosion due to the storms but also allows for storm recovery, post-storm emergency dune and/or shore construction, and planned nourishment events throughout the life of the project. Risk-based damages to structures are estimated based on the shoreline response in combination with pre-determined storm damage functions for all structure types within the project area. Uncertainty is incorporated not only within the input data (storm occurrence and intensity, structural parameters, structure and contents valuations, and damage functions) but also in the applied methodologies (probabilistic seasonal storm generation and multiple iteration, life cycle analysis). Results from multiple iterations of the life cycle can be averaged or presented as a range of possible values.

The project site itself is represented by divisions of the shoreline referred to as "Reaches." Because this term may also be used to describe segments of the shoreline to which project alternatives are applied, Beach-*fx* reaches will be referred to in this appendix as "model reaches." Model reaches are contiguous, morphologically homogenous areas that contain groupings of structures (residences, businesses, walkovers, roads, etc.), all of which are represented by damage elements (DEs). DEs are grouped within divisions referred to as Lots.

Figure A-23 shows a graphic depiction of the model setup. For further details about the specifics of Lot extents and DE groupings see the Appendix B: Economics.

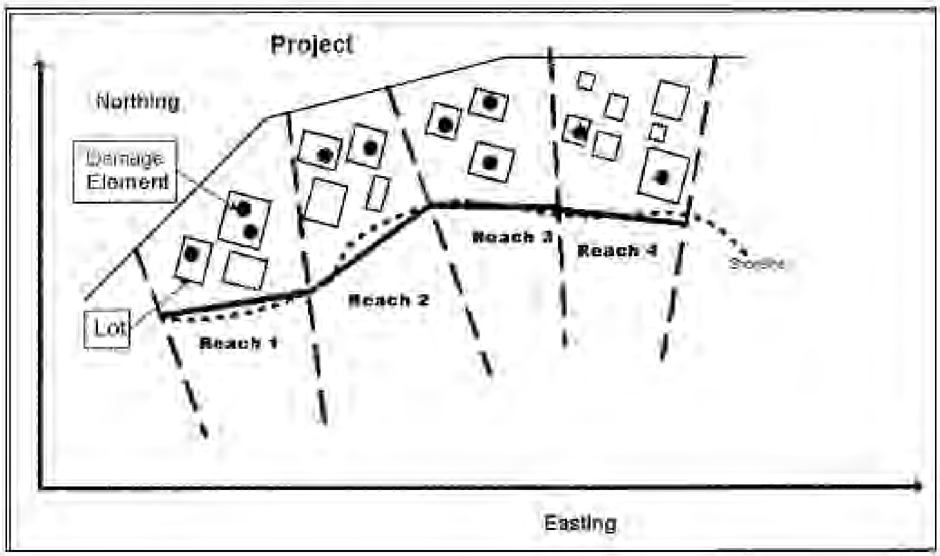


Figure A-23. Beach-*fx* Model Setup Representation

Each model reach is associated with a representative beach profile that describes the cross-shore profile of the reach. While an effort is made to designate model reaches to include a single DNR monument (FDEP R-monument) from which historical survey data can be used to establish a representative profile for that reach, the positioning of the monument within each reach and the length of each reach are variable. Multiple model reaches may share the same representative beach profile and groupings of model reaches may represent a single design reach. For the Main Segment, the project area consists of 10 representative profiles divided between 47 model reaches. Key Biscayne consists of two representative profiles divided between four model reaches. Table A-14 provides representative profiles, model reach identifiers, and the FDEP R-monument that falls within the borders of each model reach.

Implementation of the Beach-*fx* model relies on a combination of meteorology, coastal engineering, and economic analyses and is comprised of four basic elements:

- Meteorological driving forces
- Coastal morphology
- Economic evaluation
- Management measures

The subsequent discussion in this section addresses the basic aspects of implementing the Beach-*fx* model. For a more detailed description of theory, assumptions, data input/output, and model implementation refer to Gravens et al. (2007), Males et al. (2007), and USACE (2009).

Table A-14. Model Reaches

Representative Profiles	Model Reaches	R-Monuments
MD01	R028 R031 R032 R033 R034 R035 R036 R037 R038 R039 R040 R041 R042 R043 R044 R045 R046 R050 R051 R052 R061	R-28 R-31 R-32 R-33 R-34 R-35 R-36 R-37 R-38 R-39 R-40 R-41 R-42 R-43 R-44 R-45 R-46 R-50 R-51 R-52 R-61
MD02	R029 R030 R062	R-29 R-30 R-62
MD03	R047 R048 R058 R063	R-47 R-48 R-58 R-63
MD04	R049 R053 R054	R-49 R-53 R-54
MD05	R055 R056 R057	R-55 R-56 R-57
MD06	R059 R064 R065	R-59 R-64 R-65
MD07	R060	R-60
MD08	R066 R067 R068 R069 R070	R-66 R-67 R-68 R-69 R-70
MD09	R071 R072 R073	R-71 R-72 R-73
MD10	R074	R-74
KB01	R102	R-102
KB02	R104 R106 R107	R-103 / R-104 R-105 / R-106 R-107

6.2 METEOROLOGICAL DRIVING FORCES

The predominant driving force for coastal morphology and associated damages within the Beach-*fx* model is the storm suite that is applied to the life-cycle simulation. The predominant driving force for erosion, inundation, and wave damages on the eastern coast of Florida is tropical storms (hurricanes) in the summer months and extra-tropical storms (Nor'easters) in the winter months. Two different datasets were mined to develop the storm suite. FEMA has recently completed a flood map modernization project in southeast Florida. For this study, they simulated 392 synthetic tropical storms, each with an assigned probability mass. From this data, the tropical storm suite was obtained by choosing representative storms for various return periods. The FEMA storm suite does not include extra-tropical storms. To develop extra-tropical storms for the storm suite, the Ocean Weather Incorporated (OWI) extra-tropical reanalysis was used. This reanalysis included a hindcast of 48 extra-tropical storms between 1979 and 2017.

For the tropical storms, node 513028 was chosen (water level save point 53 and wave save point 131). This point is in approximately 17.4 ft NAVD88 water depth and is close to the center of the study area (25.8334° N, 80.1119° W). The FEMA study (BakerAECOM 2016) consisted of 392 storms. The return period water levels at the 90% confidence level were determined and are shown in Table A-15. Following the methodology of Sanderson and Gravens (2018), the storms were divided into clusters based on return period as shown in Table A-16. Note that the first storm cluster starts at the 10-year return interval since the two- and five-year return periods have values which are typically not damage producing. The final storm cluster, corresponding to the 1,000-year return interval, is empty as no storms produced a stage greater than 6.76 ft-NAVD88. Of the 392 storms, 202 storms had surge height at the 10-year return period or greater. The values presented in this table are not entirely consistent with the FEMA FIS values presented in Section 4.5. This is due to multiple factors, including a change in models used by FEMA in their analysis and updated statistical methodologies employed. Additionally, the offshore depths where these water elevations are presented are not consistent. The FIS presents water elevations at the shoreline, while the values shown below are at a depth of 17.4 ft NAVD88.

Table A-15. Annual Exceedance Probabilities for Tropical Storm Surge

Return Period (yrs)	Stage (ft, NAVD88)
2	----
5	1.08
10	1.74
20	2.46
50	3.51
100	4.40
200	5.15
500	6.10
1000	6.76

Table A-16. Lower and Upper Stage Limits for Tropical Storms

Lower Stage (ft-NAVD88)	Return Year/ Cluster Number	Upper Stage (ft-NAVD88)	Number of Storms
1.41	10/1	2.10	112
2.10	20/2	2.99	45
2.99	50/3	3.95	23
3.95	100/4	4.77	12
4.77	200/5	5.62	6
5.62	500/6	6.43	4
6.43	1,000/7		0

After the storms have been assigned to the storm clusters, the storm surge hydrograph time series of all storms in each cluster are translated along the time axis such that peak surge is aligned at a single time. For clusters with large numbers of storms, in the higher frequency clusters the storms were further sub-divided into groups based on the duration of the hydrograph. To do this, the storms were examined to determine how long the water level exceeded the minimum value in the cluster. Based on this value, the storms were subdivided into short duration (or highly peaked), long duration, and average duration events. The short duration events were at least one standard deviation shorter than the mean, while the long duration events were at least one standard deviation greater. For the final cluster, which featured four storms, all were carried forward into the storm suite.

The final step is the calculation of the relative probability to be assigned to each of the selected representative storms. This information is required input into Beach-*fx* which will use the specified relative probability data when sampling specific storms from the input storm suite. The relative probability of a selected representative storm is computed by summing the relative probabilities of all the storms in the storm cluster that that storm represents. The 19 selected tropical storms and their associated probabilities are shown in Table A-17.

Table A-17. Selected Representative Tropical Storms and Relative Probabilities

Cluster Number	Representative Storm Number	Relative Probability	Number of Storms Represented	Note
1	69	0.069883	77	Average
1	171	0.018238	21	Peaked
1	383	0.017148	14	Long
2	78	0.030579	29	Average
2	170	0.006986	9	Peaked
2	256	0.007793	7	Long
3	72	0.009315	14	Average
3	110	0.002585	4	Long
3	172	0.002776	5	Peaked
4	62	0.000723	2	Peaked
4	76	0.003582	7	Average
4	107	0.002637	3	Long
5	60	0.000915	3	Average
5	89	0.000418	1	Peaked
5	106	0.001693	2	Long
6	26	0.000418	1	Highest
6	27	0.000418	1	Long
6	61	0.000305	1	Peaked High
6	91	0.000418	1	Peaked Low

For the extra-tropical storms, a similar methodology was used. However, the FEMA storm database only considered tropical storms. To supplement this data void, the OWI extra-tropical reanalysis (Parsons et al. 2018) was used. This study used a similar coupled hydrodynamic-wave modeling system to model historical tropical storms. The record extends from 1979 to 2017 and contains 48 storms affecting Miami-Dade County (48 storms over 39 years, 1.23 storms/year). The OWI save-point is located approximately 1.4 miles northeast of the FEMA save-point in 35.2 feet NAVD88 water depth. This is the closest/shallowest save point to the FEMA point. Using linear wave theory, the wave height was transformed to a value consistent with the FEMA save-point depth. The extra-tropical storms in the hindcast rarely generate surge heights greater than the five- to 10-year return period. However, they do produce large wave heights offshore. In this way, wave height is a good proxy for determining representative storms to populate the storm suite.

The OWI extra-tropical database was compared with the USACE WIS hindcast, and it was evident that the OWI database only included selected storms over the 39-year period. The WIS database shows approximately 330 storms in the 1980 to 2014 record with waves heights greater than a peak over threshold value of 5.77 feet (the mean plus two standard deviations). Unfortunately, the WIS database which is continuous over the 34-year record only includes waves characteristics. The OWI database, which only includes the 48 selected events, includes both wave and surge components. As a result, the WIS database was used to develop the probabilistic analysis and determine the return period storm clusters, and storms from the OWI database were used to populate the clusters. The WIS storms were divided into two clusters, those between 5.25 and 7.50 feet and those greater than 7.50 feet as shown in Table A-18. This breaks down to the higher frequency storms and those with a return period exceeding five years. Within those two clusters, three storms from the OWI database were chosen. Those storms and their associated relative probabilities are shown in Table A-19.

Table A-18. Extra-Tropical Storm Clusters

Lower Wave (ft)	Cluster Number	Upper Wave (ft)	Number of Storms
5.25	1	7.50	132
7.50	2	---	77

Table A-19. Chosen Extra Tropical Storms and their Assigned Relative Probabilities

Cluster Number	Representative OWI Storm Number	Relative Probability	Number of Storms Represented
1	24	0.3157895	66
1	35	0.3157895	66
2	17	0.3684211	77

Because these events can be of limited duration, passing over a given site within a single portion of the tide cycle, it is assumed that any of the storms could have occurred during any combination of tidal phase and tidal range. Therefore, each of the plausible storm hydrographs was combined with possible variations in the astronomical tide. This was achieved by combining the peak of each storm surge hydrograph with the astronomical tide at high tide, mean tide falling, low tide, and mean tide rising for each of three tidal ranges corresponding to the lower quartile, mean, and upper quartile tidal ranges. This resulted in 12 distinct combinations for each of the 19 tropical and three extra-tropical storms and a total of 264 storm conditions in the plausible storm dataset.

In addition to the plausible storm dataset, the seasonality of the storms must also be specified. The desired storm seasons assume that each plausible storm takes place within the season in which the original historical storm occurred. For synthetic storms, this assumption breaks down. To reconcile this, two broad seasons were defined, one for tropical storms and one for extra-tropical storms. Probability is defined for each season through the probability parameter. The probability parameter is determined for each season and storm type by dividing the number of storms by the total number of years in the storm record for the historical storms and is defined by the storm occurrence rate for the tropical storms. Two storm seasons were specified for Miami-Dade County (Table A-20).

Table A-20. Miami-Dade County Beach-*fx* Storm Seasons

Storm Season	Start Date	End Date	Tropical	Extra-Tropical
			Probability	Probability
Tropical Storms	June 1	Nov 30	0.366	0.000
Extra-tropical Storms	Dec 1	May 31	0.000	5.971

The combination of the plausible storm datasets and the specified storm season allows the Beach-*fx* model to randomly select from storms of the type that fall within the season currently being processed. For each storm selected, a random time within the season is chosen and assigned as the storm date. The timing of the entire sequence of storms is governed by a pre-specified minimum storm arrival time. A minimum arrival time of 14 days was specified for Miami-Dade County. Based on this interval, the model attempts to place subsequent storm events outside of a 28-day window surrounding the date of the previous storm (i.e., a minimum of 14 days prior to the storm event and a minimum of 14 days following the storm event). The model does allow the user to set different minimum arrival times for extra-tropical and tropical storms. Due to the probabilistic nature of the model, the minimum arrival time may be overridden as warranted during the life-cycle analysis.

6.3 COASTAL MORPHOLOGY

The Beach-*fx* model estimates changes in coastal morphology through four primary mechanisms:

- Shoreline storm response
- Applied shoreline change
- Project-induced shoreline change
- Post-storm berm recovery

Combined, these mechanisms allow for the prediction of shoreline morphology for both with and without project conditions.

6.3.1 SHORELINE STORM RESPONSE

Shoreline storm response is determined by applying the plausible storm set that drives the Beach-*fx* model to simplified beach profiles that represent the shoreline features of the project site. For this study, the application of the storm set to the idealized profiles was accomplished with the CSHORE coastal processes response model (Johnson et al. 2012). CSHORE is a numerical model which simulates storm-induced beach change based on storm conditions, initial profiles, and shoreline characteristics such as beach slope and grain size. Output consists of post-storm beach profiles, maximum wave height and wave period information, and total water elevation including wave setup. Pre- and post-storm profiles, wave data, and water levels can be extracted from CSHORE and imported into the Beach-*fx* Shore Response Database (SRD). The SRD is a relational database used by the Beach-*fx* model to pre-store results of CSHORE simulations of all plausible storms impacting a pre-defined range of anticipated beach profile configurations.

6.3.1.1 Idealized Representative Profiles

To develop the idealized CSHORE profiles from which the SRD was derived, it was necessary to first develop representative profiles for the project shoreline. The number of representative profiles developed for any given project depends on the natural variability of shoreline itself. Historical profiles at each FDEP R-monument were compared over time, aligned, and then averaged into a composite profile representative of the shoreline shape at that given R-monument location. Composite profiles are then compared and separated into groupings according to the similarity between the following seven dimensions:

- Upland elevation
- Dune slope
- Dune height
- Dune width
- Berm height
- Berm width
- Foreshore slope

6.3.1.2 Future Without Project (FWOP) Profiles

The economic base year for the present study is 2026. The model start year is 2025. Shoreline erosion between 2021 and 2025 was simulated using Beach-*fx* and the average 2025 profiles were used with a 2025 start year for the FWOP modeling. The 2021 starting shoreline position had dune dimensions based on the 2018 beach monitoring survey and berm widths based on the estimated equilibrated supplemental post-nourishment berm widths expected to be present in 2021. The projected 2025 shoreline for Key Biscayne was developed from an amalgamation of surveys from 2016 to 2019 considering average erosion rates.

Using the surveys, ten representative profiles were developed for the Main Segment. For Key Biscayne, two additional representative profiles were developed. Using the representative profiles, idealized profiles representing the major dimensions of the profile were defined. Table A-21 provides dimensions for each of the idealized pre-storm Beach-*fx* profiles.

Table A-21. Dimensions of Idealized Representative Profiles - Miami-Dade County

Idealized Profile	Model Reach	Upland Elevation (ft-NAVD88)	Dune Elevation (ft-NAVD88)	Dune Width (ft)	Berm Elevation (ft-NAVD88)	Berm Width (ft)
MD01	R028, R031, R032 R033, R034, R035 R036, R037, R038 R039, R040, R041 R042, R043, R044 R045, R046, R050 R051, R052, R061	4	11	60	7	30
MD02	R029, R030, R062	6	9	60	7	40
MD03	R047, R048 R058, R063	7	10	30	7	170
MD04	R049, R053, R054	6	10	70	6	40
MD05	R055, R056, R057	5	10	40	7	80
MD06	R059, R064, R065	4	10	80	6	240
MD07	R060	3	10	50	7	30
MD08	R066, R067, R068 R069, R070	6	14	50	6	170
MD09	R071, R072, R073	6	12.5	40	6.5	180
MD10	R074	7	16	20	6.5	20
KB01	R102	4	9	40	4	40
KB02	R104, R106, R107	4	8	40	3	10

6.3.1.3 CSHORE Methodology

CSHORE simulates beach profile changes that result from varying storm waves and water levels. These beach profile changes include the formation and movement of major morphological features such as longshore bars, troughs, and berms.

CSHORE is a one-dimensional profile evolution model designed to predict waves, currents, and bed-evolution in the nearshore. The CSHORE domain assumes a shore-perpendicular (cross-shore) transect with uniform grid spacing. A foundational assumption of CSHORE is alongshore uniformity, although obliquely incident waves and longshore currents are included.

The governing equations are a combination of the time-averaged, depth-integrated continuity, cross-shore and alongshore momentum, wave action, and roller energy equations. The bed shear stresses in the momentum equations are modeled with a quadratic friction formulation, including a user-entered friction coefficient (Cd = 0.015 for simulations presented herein), and the radiation stress terms are estimated with linear progressive wave theory (Dean and Dalrymple 1991). The dissipation in the wave energy equation is modeled using the Battjes and Stive (1985) formula as modified by Kobayashi et al. (2005). The roller energy equation is that of Ruessink et al. (2001) for the case of alongshore uniformity, where the roller dissipation is given by the empirical relationship in Kobayashi et al. (2005).

CSHORE models the sediment transport, deposition, and erosion with a combination of the Kobayashi and Johnson (2001) suspended sediment model and the Kobayashi et al. (2008a) bedload transport formula, using the critical Shields parameter to estimate incipient sediment motion (Madsen and Grant 1976). Following Kobayashi et al. (2008b), CSHORE also incorporates empirical formulas to account for irregular wave runup, overtopping, and seepage, as well as a probabilistic model of the intermittently wet/dry zone to predict wave runup and overwash.

Once applied, output data consists of a final calculated profile at the end of the simulation, maximum wave heights, maximum total water elevations plus setup, maximum water depth, volume change, and a record of various coastal processes that may occur at any time-step during the simulation (accretion, erosion, over-wash, boundary-limited run-up, and/or inundation).

6.3.1.4 *CSHORE Calibration and Verification*

Calibration of the CSHORE model was performed using wave height, wave period, and water-level information from Hurricane Matthew (2016) (Figure A-24). Calibration of the model is required to ensure that the CSHORE model is tuned to provide realistic shore responses that are representative of the specific project location.

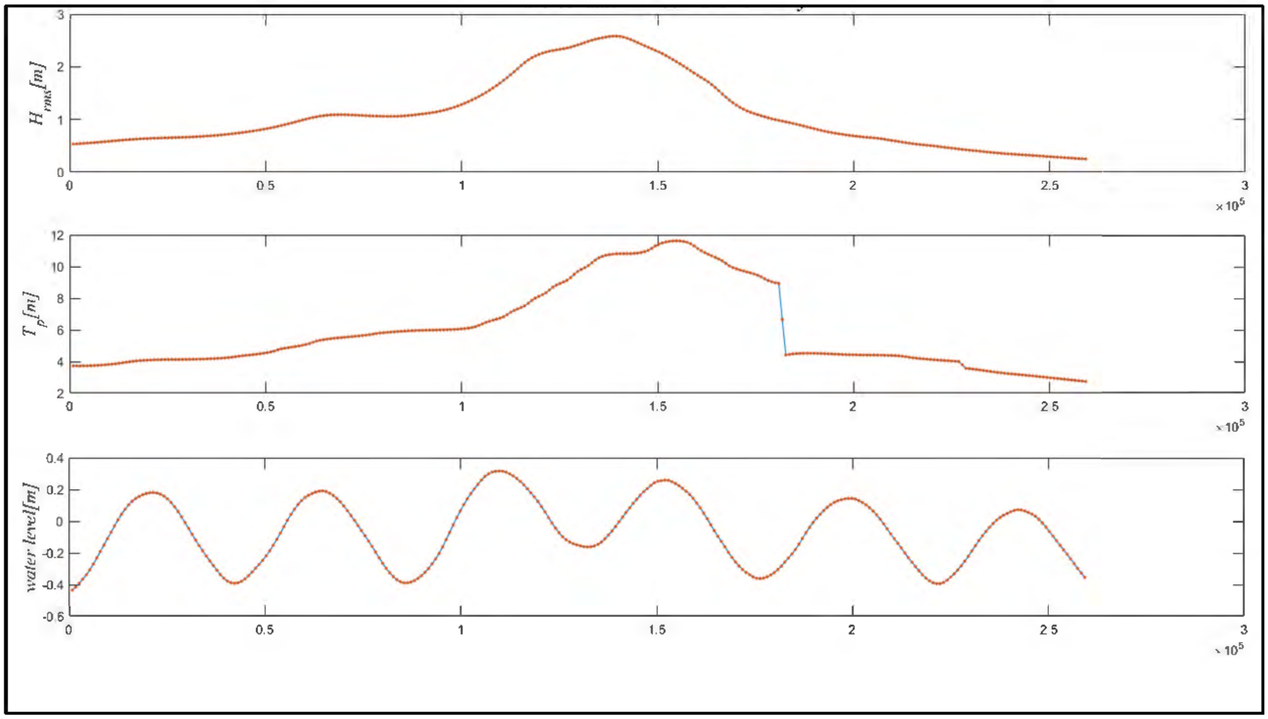


Figure A-24. Hurricane Matthew Wave Height and Period and Water Level at the CSHORE Seaward Model Boundary for Calibration

Pre- and post-storm shoreline profiles were obtained from FDEP. Using the pre-storm profiles, CSHORE was then run with a range of values for an array of calibration parameters. Table A-22 provides the relevant beach characteristic and sediment transport calibration parameters as well as their final (best fit) calibrated values. Calibration parameters were verified using wave height, wave period, and water-level information from Hurricane Irma (2017) (Figure A-25). Figure A-26 to Figure A-32 show a sample of the verification CSHORE outputs. Verification of the CSHORE outputs was only conducted for the Main Segment because the Key Biscayne Segment was not initially included. The CSHORE model for Key Biscayne used the same model parameters as the Main Segment, with an adjustment in the grain size.

Table A-22. CSHORE Calibrated Beach Characteristic and Sediment Transport Parameters

Parameter	Range	Optimal Value
Median Sediment Grain Size (d_{50})	0.15 - 1.51 mm	0.47 mm
Suspension Efficiency due to Breaking (e_B)	0.002 - 0.008	0.005
Suspended Load Parameter (a)	0.1 - 0.5	0.2
Bedload Parameter (b)	0.001 - 0.002	0.001

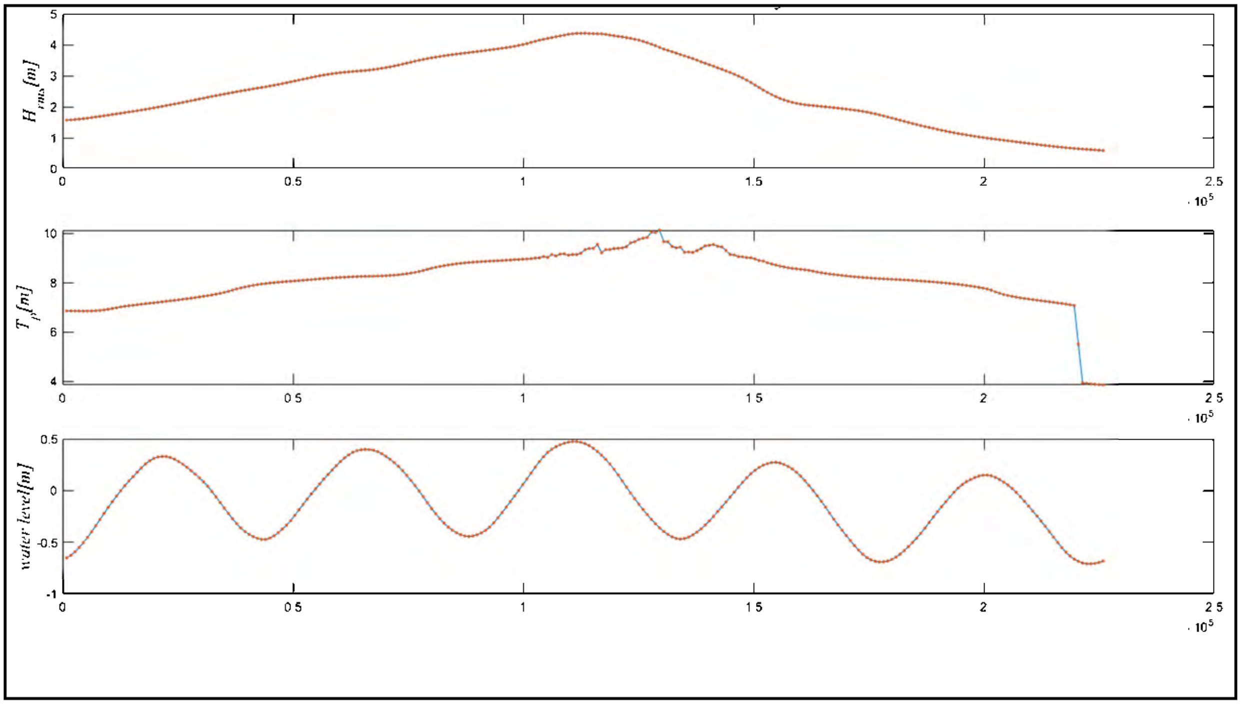


Figure A-25. Hurricane Irma Wave and Water Level Data for CSHORE Verification

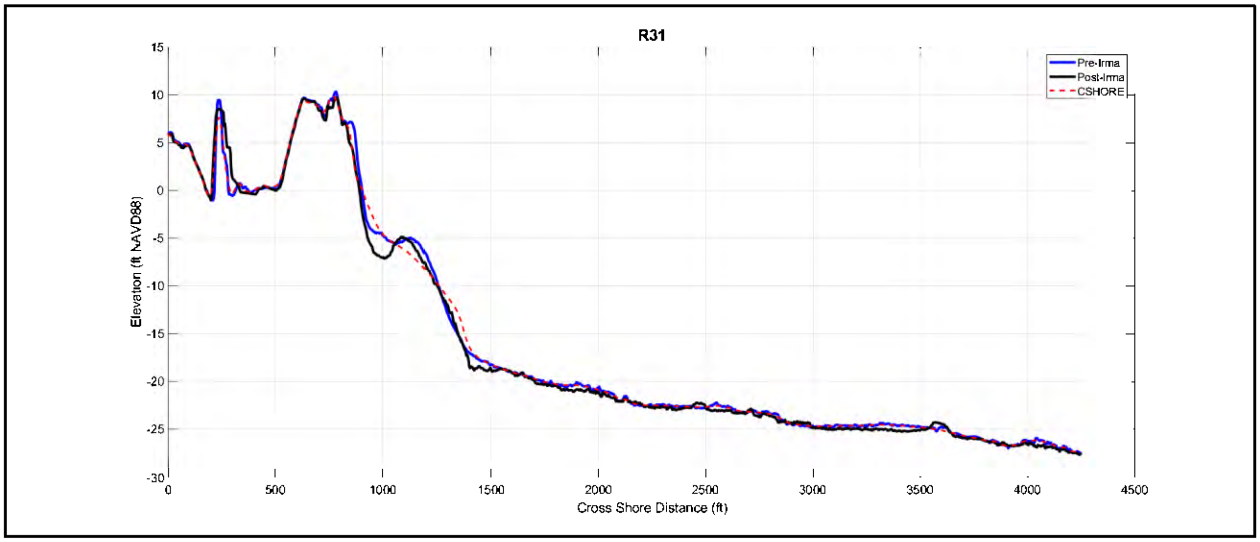


Figure A-26. CSHORE Verification at R-31 (Hurricane Irma)

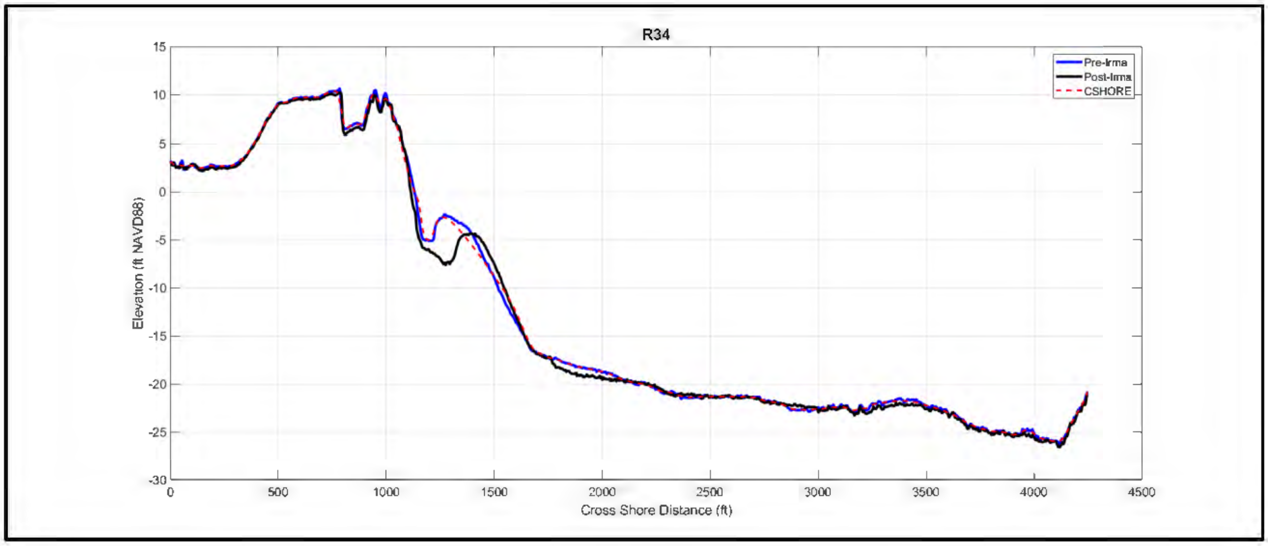


Figure A-27. CSHORE Verification at R-34 (Hurricane Irma)

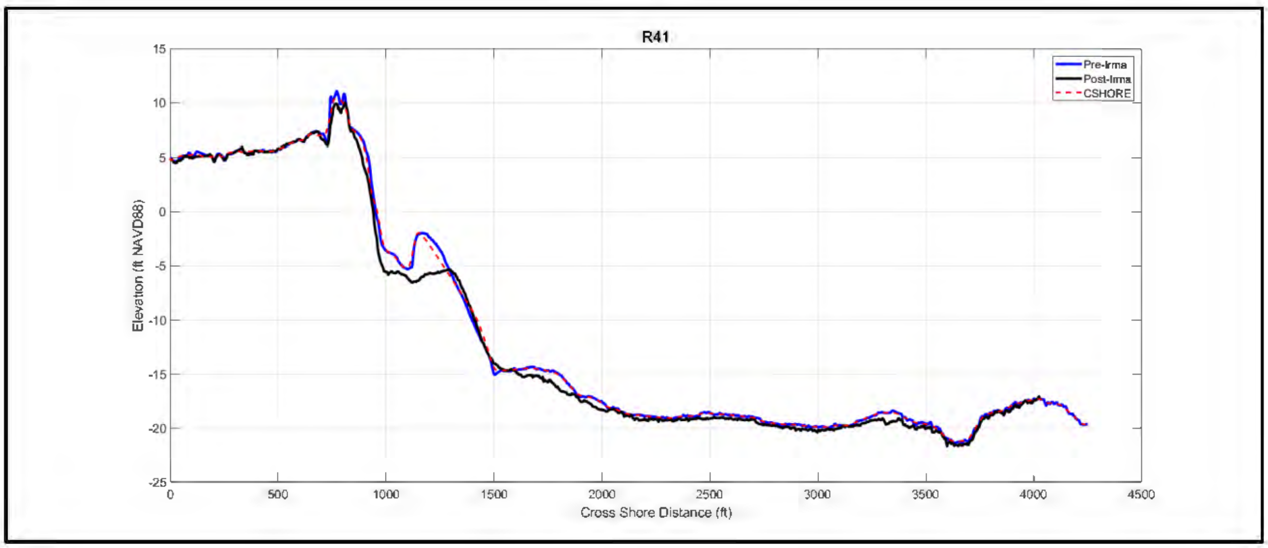


Figure A-28. CSHORE Verification at R-41 (Hurricane Irma)

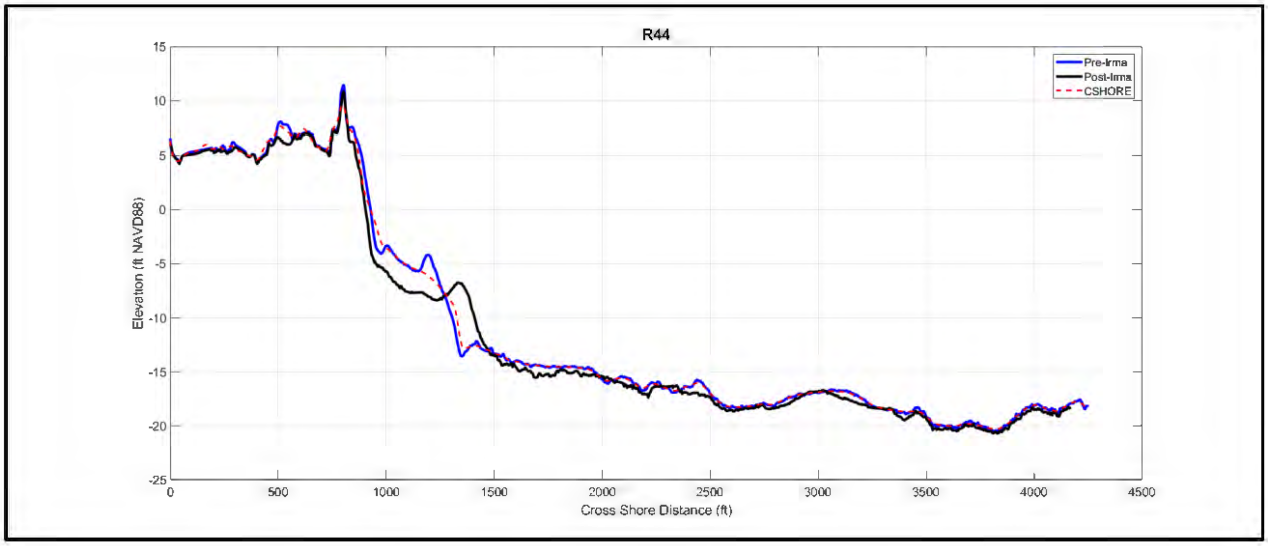


Figure A-29. CSHORE Verification at R-44 (Hurricane Irma)

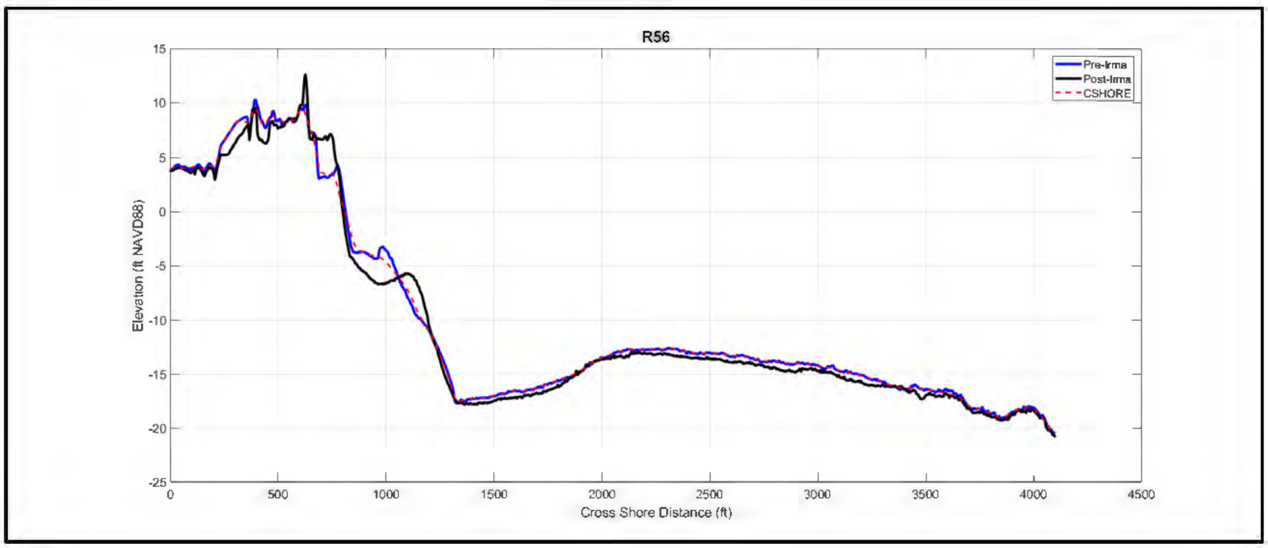


Figure A-30. CSHORE Verification at R-56 (Hurricane Irma)

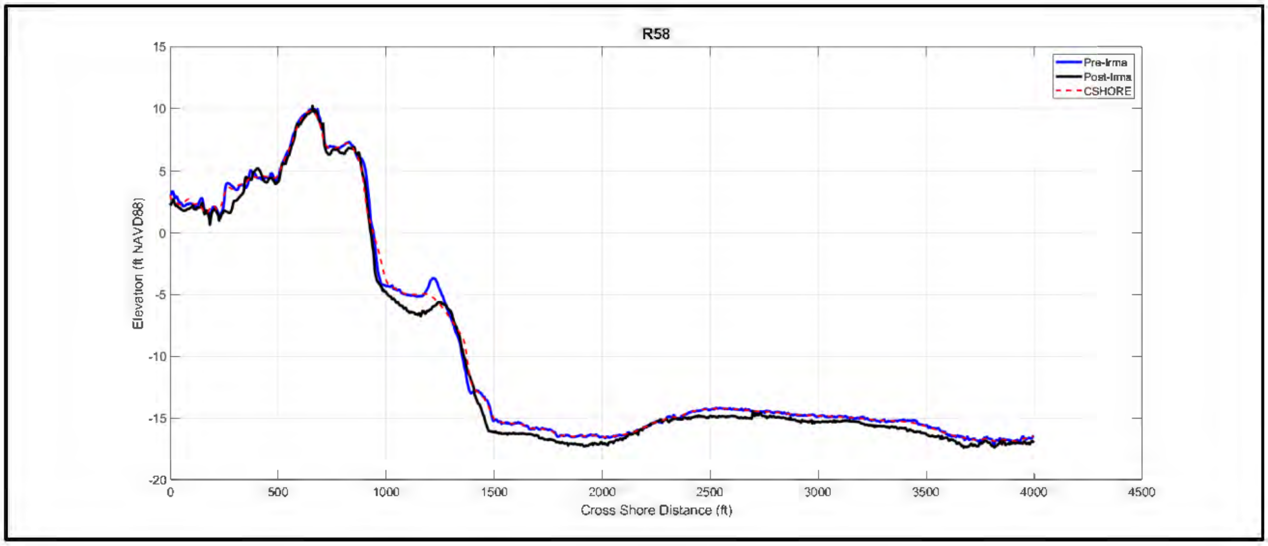


Figure A-31. CSHORE Verification at R-58 (Hurricane Irma)

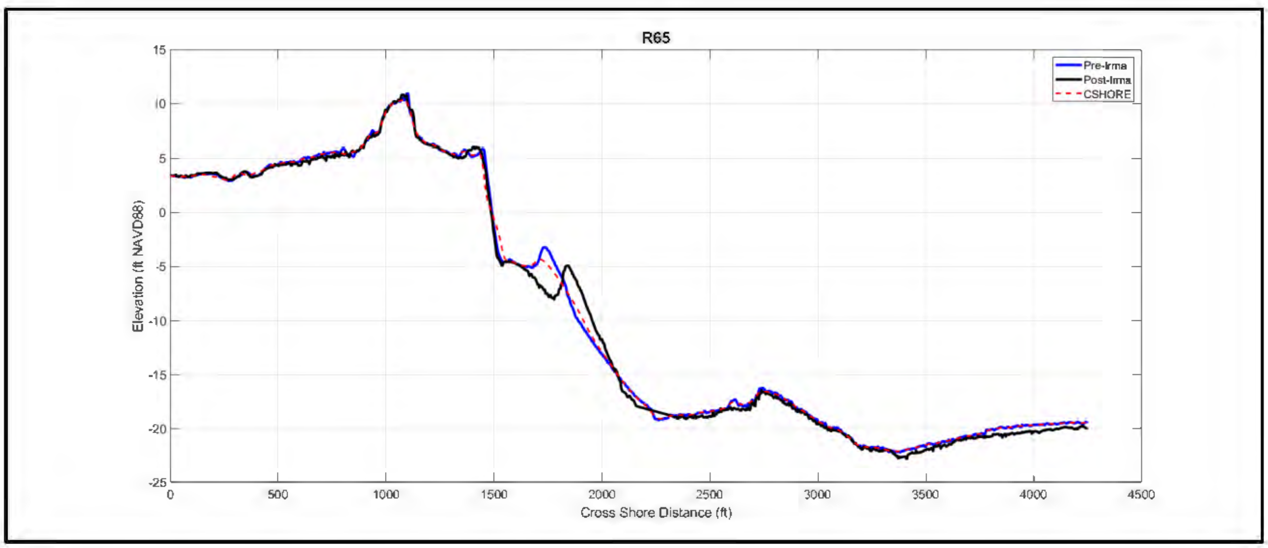


Figure A-32. CSHORE Verification at R-65 (Hurricane Irma)

6.3.1.5 CSHORE Simulations

Calibrated CSHORE simulations were run for an array of future-without-project and with-project (projected maximum potential dune and berm dimensions) idealized profiles in combination with each of the tropical and extra-tropical storms in the plausible storm database. This resulted in individual storm response profiles. From these profiles, changes in the key profile dimensions were extracted and stored in the Beach-*fx* SRD.

6.3.2 APPLIED SHORELINE CHANGE

The applied shoreline change rate (in feet per year) is a Beach-*fx* morphology parameter specified at each of the model reaches. It is a calibrated parameter that, combined with the storm-induced change generated internally by the Beach-*fx* model, returns the historical shoreline change rate for that location. Calibration is essential to ensure that the morphology behavior is appropriate and representative of the study area.

The target shoreline change rate is an erosion or accretion rate equivalent to the historical background shoreline change rates for the project area. Changes in mean high water (MHW) position typically provide a historical view of the behavior of the shoreline. In Florida, the FDEP, local sponsors, and USACE gather profiles. Available beach surveys for Miami-Dade County go back as far as 1873, and the most recent surveys were completed in 2021. Because both the Main Segment (starting 1975) and Key Biscayne (starting 1987) have been periodically nourished, most available surveys do not accurately reflect historical background erosion rates when examined without careful thought as to the effects of the beach fill. An inspection of available data prior to initial construction also found that early surveys did not yield reliable shoreline change rates due to the sparsity of the data both temporally and spatially.

Previous examinations of the Miami-Dade shoreline (i.e., 2016 LRR (USACE 2016)) have simply taken the most recent MHW location and compared to those in the past. This approach was initially employed in this study, but it became evident that the effects of beach nourishment were skewing the data.

For the Main Segment, countywide surveys were examined between 2005 and 2019. On a reach-by-reach basis, the longest available stretch absent the influences of beach nourishment was examined. In some cases, this was only a few years such as in Bal Harbour, in others like South Beach this was the entire 14-year period.

Initially, once this rate was determined on a reach-by-reach basis, the rates were smoothed by averaging adjacent reaches. This resulted in the higher erosion rates in the few higher erosional areas to be smoothed out into the adjacent reaches. This mimics the expected effects that would result from discontinuing the nourishment in these areas by increasing erosion in the adjacent areas. However, this methodology was found to be too effective at blending the erosion rates of the historical erosional hotspots into the adjacent reaches. During initial future-without-project (FWOP) Beach-*fx* runs, the model results did not reflect an accurate assessment of the shoreline erosion conditions. As a result, the rates of areas with large historical erosion rates, the “hot spots,” (R-44 to R-45, R-50, R-54 to R-55, and R-59 to R-61) were ultimately left without smoothing, while smoothing was applied to the rest of the Main Segment. This combination created the more representative shoreline erosion pattern for the Main Segment seen in Table A-23.

For Key Biscayne, surveys were examined between 1996 and 2019. For each reach, the background erosion rate was determined by only regarding surveys taken after the beach fill in the area was judged to have been equilibrated (more than one to two years post-fill).

In contrast to the Main Segment, where each model reach consisted of one R-monument, the model reaches for Key Biscayne contain multiple R-monuments. The erosion rates found in Table A-23 for Key Biscayne are the averaged background erosion rates for all the R-monuments within each model reach. Averaging multiple survey locations created a smoothing effect within each model reach and created a more representative shoreline within the project area. Refer to Sub-Appendix A-1 for more details on the methodology used to select the background erosion rates.

During Beach-*fx* calibration, applied erosion rates were adjusted for each model reach and the Beach-*fx* model was run repeatedly for 300 iterations for the Main Segment and for 250 iterations for the Key Biscayne Segment (the model repeatedly crashed when trying to calibrate for more than 278 iterations for Key Biscayne) over the 50-year project life cycle. Calibration is achieved when the rate of shoreline change, averaged over hundreds of life cycle simulations, is equal to the background (target) shoreline change rate. Table A-23 provides the historical background erosion rates, storm-induced change rates (isolated by running the model with applied rates set to zero), and the calibrated Beach-*fx* applied erosion rates for Miami-Dade County.

Table A-23. Historical Background Change Rates and Calibrated Beach-*fx* Applied Erosion Rates

Model Reach	Historical Background Change Rate (ft/yr)	Storm Induced Change Rate (ft/yr)	Calibrated Beach-*fx* Applied Erosion Rate (ft/yr)
R028	-11.45	-1.39	-10.06
R029	-14.70	-0.57	-14.12
R030	-14.91	-0.57	-14.33
R031	-10.56	-1.39	-9.17
R032	-6.78	-1.39	-5.39
R033	-4.21	-1.39	-2.82
R034	-3.52	-1.39	-2.13
R035	-1.35	-1.39	0.04
R036	-1.21	-1.39	0.18
R037	-0.73	-1.39	0.66
R038	-0.18	-1.39	1.21
R039	-1.24	-1.39	0.15
R040	-3.22	-1.39	-1.83
R041	-6.64	-1.39	-5.25
R042	-6.66	-1.39	-5.27
R043	-6.46	-1.39	-5.07
R044	-10.86	-1.39	-9.47
R045	-14.56	-1.39	-13.17
R046	-8.83	-1.39	-7.44
R047	-6.02	-0.47	-5.55
R048	-10.87	-0.47	-10.40
R049	-11.52	-1.30	-10.22
R050	-9.85	-1.39	-8.46
R051	-9.65	-1.39	-8.26
R052	-2.22	-1.39	-0.83
R053	-3.17	-1.30	-1.87
R054	-12.25	-1.30	-10.95
R055	-8.71	-0.39	-8.31
R056	-2.99	-0.39	-2.60
R057	0.22	-0.39	0.61
R058	1.68	-0.47	2.14
R059	-0.37	-2.64	2.27
R060	-0.57	-0.08	-0.48
R061	-6.80	-1.39	-5.41
R062	-4.99	-0.57	-4.41
R063	-4.24	-0.47	-3.77
R064	-2.95	-2.64	-0.31
R065	-1.11	-2.64	1.53
R066	1.36	-1.48	2.84
R067	3.29	-1.48	4.77
R068	4.74	-1.48	6.22
R069	5.29	-1.48	6.77
R070	4.97	-1.48	6.45
R071	4.90	-0.79	5.69
R072	5.31	-0.80	6.10
R073	5.47	-0.79	6.27
R074	5.46	-0.09	5.55
R102	-1.60	-3.82	2.22
R104	-2.80	-4.90	2.10
R106	-1.70	-4.10	2.40
R107	-0.10	-7.19	7.09

6.3.3 POST-STORM BERM RECOVERY

Post-storm recovery of eroded berm width after the passage of a major storm is a recognized process. Although present coastal engineering practice has not yet developed a predictive method for estimating this process, it is an important element of post-storm beach morphology. Within Beach-*fx*, post-storm recovery of the berm is represented in a procedure in which the user specifies the percentage of the estimated berm width loss during the storm that will be recovered over a given recovery interval. It is important to note that the percentage itself is not a "stand alone" parameter that is simply applied during the post storm morphology computations. The percentage of berm recovery is estimated prior to model calibration and becomes a tunable calibration parameter to ensure model convergence (when the model reproduces the target erosion rates as discussed in Section 6.3.2: Applied Shoreline Change).

Based on recommendations by the model developer regarding Florida shorelines, review of available historical FDEP profiles that would qualify as pre- and post-storm and successful model calibration, a recovery percentage of 90% over a recovery interval of 21 days was determined to be appropriate for Miami-Dade County.

6.4 ECONOMIC EVALUATION

The Beach-*fx* model analyzes the economics of shore protection projects based on the probabilistic nature of storm-associated damages to structures in the project area. Damages are treated as a function of structure location and construction, the intensity and timing of the storms, and the degree of protection that is provided by the natural or constructed beach. Within the model, damages are attributed to three mechanisms:

- Erosion (through structural failure or undermining of the foundation)
- Flooding (through structure inundation levels)
- Waves (through the force of impact)

Although wind may also cause shoreline damage, shore protection projects are not designed to mitigate for impacts due to wind. Therefore, the Beach-*fx* model does not include this mechanism.

Damages are calculated for each model reach, lot, and damage element following each storm that occurs during the model run. Erosion, water level, and maximum wave height profiles are determined for each individual storm from the lookup values in the previously stored SRD. These values are then used to calculate the damage driving parameters (erosion depth, inundation level, and wave height) for each damage element.

The relationship between the value of the damage driving parameter and the percent damage incurred from it is defined in a user-specified “damage function.” Two damage functions are specified for each damage element, one to address the structure and the other to address its contents. Damages due to erosion, inundation, and wave attack are determined from the damage functions and then used to calculate a combined damage impact that reduces the value of the damage element. The total of all FWOP damages is the economic loss that can be mitigated by the CSRM project.

A thorough discussion of the economic methodology and processes of Beach-*fx* can be found in Appendix B: Economics.

6.5 MANAGEMENT MEASURES

Shoreline management measures that are provided for in the Beach-*fx* model are emergency nourishment and planned nourishment.

6.5.1 EMERGENCY NOURISHMENT

Emergency nourishments are generally limited beach fill projects conducted by local governments in response to storm damage. The Main Segment in Miami-Dade County does not have a consistent history of emergency nourishment in response to storm-related erosion. Local nourishments do occur but are episodic and cannot be relied upon in a consistent way. Therefore, no emergency management measure was included in the Beach-*fx* analysis for the Main Segment.

The Key Biscayne Segment has a history of local and emergency nourishments after storm damage. Emergency nourishment was used in both the FWOP and FWP Beach-*fx* model runs to simulate these events. Any reduction in emergency nourishment in the FWP runs compared to the FWOP runs was counted towards the benefits for the project.

6.5.2 PLANNED NOURISHMENT

Planned nourishments are handled by the Beach-*fx* model as periodic events based on nourishment templates, triggers, and nourishment cycles. Nourishment templates are specified at the model reach level and include all relevant information such as order of fill, dimensions, placement rates, unit costs, and borrow-to-placement ratios. Planned nourishments occur when user-defined nourishment triggers are exceeded, and a mobilization threshold volume is met. At a pre-set interval, all model reaches which have been identified for planned nourishment are examined. In reaches where one of the nourishment threshold triggers is exceeded, the required volume to restore the design template is computed. If the summation of individual model reach level volume requirements (to fill the given nourishment template) exceeds the mobilization threshold volume established by the user, then a nourishment is triggered, and all model reaches identified for planned nourishment are restored to the nourishment template.

6.5.2.1 Nourishment Distance Triggers and Mobilization Threshold

Beach-*fx* planned nourishment templates have three nourishment distance triggers, berm width, dune width, and dune height. Each distance trigger is a fractional amount of the corresponding nourishment template dimension. When the template dimensions fall below the fraction specified by the trigger, a need for renourishment is indicated. For any project template, the berm width trigger can be set such that a minimum berm width (what has been traditionally referred to as a “design berm”) can be maintained, allowing the remainder of the template to act as sacrificial fill (traditionally referred to as “advance fill”), or the berm trigger can be set to allow minimal erosion of the berm allowing the project interval and mobilization threshold volume to govern the renourishment cycle. For the Miami-Dade study, the latter method was employed, and the berm trigger was set to 0.99 (1% loss). The dune width and dune height triggers were similarly set to allow minimal erosion to the dune. The dune width and dune height triggers were set to 0.99 (1% loss of width) and 0.90 (10% loss of height), respectively.

6.5.2.2 Project Interval Setting and Mobilization Threshold

The project interval (set in years) is the interval at which the Beach-*fx* model will determine if a renourishment is required. At the set interval, if nourishment triggers have been met, the model will then determine the volume in each reach designated to receive fill that would be necessary to restore the full nourishment template for that reach. If the sum of the individual reach volumes exceeds the user-specified mobilization threshold, a renourishment event is initiated. If the total volume falls below the mobilization threshold, no event is initiated, and the model will not evaluate the nourishment triggers again until the next interval increment. For example, a project interval of four years will cause the model to evaluate nourishment distance triggers in year four of the project life, and if the triggers or volume threshold are not met, the model will not evaluate the triggers again until year eight.

The mobilization threshold (minimum nourishment volume required to initiate a nourishment cycle) is specified in cubic yards. It is often set to be approximately the same volume (or slightly less) than the volume of the sacrificial portion of the nourishment template. This allows the berm width trigger and mobilization threshold to act together to maintain a desired project dimension.

While both the project interval and the mobilization threshold are variable, one or the other will be the dominate parameter in determining the characteristics of the renourishment event.

Setting the project interval to one year allows the volume threshold to control when an event will be initiated by causing the model to check reach volume requirements on an annual basis. Renourishment events over the lifecycle may then occur during any given year should volumetric losses require it. Due to the random generation of storms, this can result in a range of renourishment intervals over the life of the project. In defining the project, an average renourishment interval is determined based on events occurring over multiple iterations of the project lifecycle. Deviations from the mean may be warranted to reduce risks, especially when net project benefits are equal between a more frequent and less frequent nourishment interval alternative.

When the project interval is set to a value greater than one, and the volume threshold is set low (in the range of 10,000 cubic yards), it is the interval that will determine the characteristics of the renourishment event. In this case, the model will return volumetric requirements for the specified interval.

It is the nature of the Beach-*fx* model that if the project volume is relatively fixed (volume threshold governs) then the renourishment interval becomes more variable. Conversely, if the renourishment cycle is fixed (project interval governs) then the renourishment volume becomes more variable. In practice, the best way to optimize a project is to allow either the project interval or the threshold volume to govern. Once the project alternatives have been screened (using either approach) based on performance and economic benefit, the project returning the highest net benefits may be further refined as necessary by making incremental adjustments to either the threshold volume (in cases where the project interval governs) or the project increment (in cases where the volume threshold governs). Attempting to vary the project interval and the threshold volume simultaneously during the initial screening process is not recommended as it will lead to an unreasonably large array of alternatives.

The user determines the choice of screening process, and several factors may influence the choice. At project sites where frequent high-intensity storms dominate erosional impacts, it may be preferred to determine volume losses on an annual basis. The project interval would then be set to one and the volume threshold would be determined based on the dimensions of fill (roughly equivalent the "sacrificial" portion of the fill). At project sites where storms are less frequent or less intense and erosional impacts are dominated by relatively constant conditions, including inlet effects, it may be preferred to evaluate project performance based on a fixed interval. The volume threshold would be set low (10,000 cubic yards generally) and the project interval would be set based on factors such as borrow site recharge estimates or anticipated funding cycles. Note that the choice of process and specified parameters are project specific and may vary from location to location.

Miami-Dade County lies off the east coast of Florida. Erosional losses in the Main Segment are dominated by localized (non-storm generated) sediment transport processes. The net longshore drift in the Main Segment is from north to south. The highest erosion rates are at the north end of the project area due to the inlet effects from Bakers Haulover Inlet and at several hotspot areas due to the angle of the shoreline. The south part of the project area is accretional as the Government Cut north jetty traps the material. In Key Biscayne, the erosion rate is higher at the center of the project area than at either end as material erodes from the center towards both the north and the south. The erosion rates for Key Biscayne are dominated by storm effects as localized erosion is minimal.

The project interval for both the Main Segment and Key Biscayne was set to one year. In this configuration, the model checks every year to determine if the minimum volume threshold and distance triggers are met. This allows for volume threshold to govern the characteristics of the nourishments and allows for the model to simulate nourishments when they are needed rather than at a set time interval

6.6 BEACH-*FX* PROJECT ALTERNATIVES

To determine the most effective and cost-effective CSRM strategies for the Miami-Dade Main Segment and Key Biscayne, alternatives were developed by combining model reaches and risk management strategies.

Due to the length of the shoreline, the Main Segment was divided into three planning reaches (PR) for Beach-*fx* modeling. Planning Reach 1 (PR1) is 2.5 miles long and extends from the south jetty of Bakers Haulover Inlet at R-27 to R-39.3. PR1 includes the Village of Bal Harbour and the Town of Surfside segments from the existing Miami-Dade County BEC&HP Project. PR2 extends from R-39.3 to R-56.5 (3.4 miles). This area is the northern part of Miami Beach. PR3 extends 3.5 miles from R-56.5 to the Government Cut north jetty (R-74). This area includes the southern part of Miami Beach. The Main Segment was divided for the Beach-*fx* modeling but will have one combined tentatively selected plan (TSP). In addition to the three planning reaches in the Main Segment, a fourth planning reach (PR4) was also modeled. PR4 is for Key Biscayne and extends from R-101.3 to R-108 (1.2 miles). This PR will have a separate TSP.

Beach-*fx* project alternatives were developed separately for each of the four planning reaches. Project alternatives include various sizes of beach nourishment templates, erosion control structures (ECS), existing structure modification, and dunes with reinforced cores. Beach-*fx* was then used to determine the most cost-effective alternative using 50-iteration model runs considering the high rate of SLC. The TSP will be evaluated against the other USACE SLC curves in conformance with ER 1100-2-8162.

6.6.1 MAIN SEGMENT ALTERNATIVES

6.6.1.1 Planning Reach 1 (PR1)

PR1 extends from the south jetty of Bakers Haulover Inlet at R-27 to R-39.3. A total of six Beach-*fx* alternatives were modeled for PR1. These alternatives include three different sized beach nourishment templates and the same three beach nourishment templates with the presence of ECSs. Table A-24 summarizes the six alternatives modeled for PR1.

Three dimensions define Beach-*fx* planned nourishment templates: the template dune height, template dune width, and template berm width. Berm elevations and dune and foreshore slopes remain constant based on the existing profiles.

The smallest beach nourishment template includes a dune crest elevation of 9.5 feet NAVD88, a dune crest width of 20 feet, and a berm width of 10 feet. The dune crest elevation of 9.5 feet NAVD88 and dune crest width of 20 feet are approximately equal to the existing dune elevation constructed as part of the existing Miami-Dade BEC&HP project. The berm width of 10 feet represents the minimum template that would reasonably be built for this planning reach based on the historically maintained beach (after considering project equilibration). This beach nourishment template was used in Beach-*fx* models Alternative 1 and Alternative 4.

The medium beach nourishment template includes a dune crest elevation of 9.5 feet NAVD88, a dune crest width of 20 feet, and a berm width of 25 feet. This template represents the approximate typical beach template constructed based on the historically maintained beach (after considering project equilibration). This beach nourishment template was used in Beach-*fx* models Alternative 2 and Alternative 5.

The large beach nourishment template includes a dune crest elevation of 13 feet NAVD88, a dune crest width of 20 feet, and berm width of 75 feet. This template represents the largest beach template that would likely be constructed in this planning reach based on historical construction events (after considering project equilibration). This beach nourishment template was used in Beach-*fx* models Alternative 3 and Alternative 6.

In addition to the three beach nourishment templates, ECSs were considered as an alternative in PR1. Structures such as groins and breakwaters can stabilize the shoreline and reduce nourishment rates and volumes needed in PR1. ECSs were modeled in Beach-*fx* in conjunction with the three beach nourishment templates in Alternative 4, Alternative 5, and Alternative 6.

Erosion control structures were modeled in Beach-*fx* by changing the applied shoreline change rates within the model for model reaches R028 through R038 to simulate the impact of the ECS within PR1. Changing the applied shoreline change rate allows the impacts of the ECS to be simulated without specifying the type of ECS used. This gives the user flexibility in selecting the specific type of ECS to construct. The types of ECS considered in PR1 were breakwaters (submerged, emergent, and attached) and rubble mound groins. The average annual equivalent (AAEQ) net benefit values shown in Table A-24 are reflective of costs which include groins instead of breakwaters, as explained in Section 6.7.1: Main Segment Tentatively Selected Plan. Section 6.7.1 also includes a preliminary design of the groins.

Table A-24. Planning Reach 1 Beach-*fx* Modeled Alternatives

Alternative	Description	Dune Crest Elevation (ft-NAVD88)	Dune Crest Width (ft)	Berm Width (ft)	AAEQ Net Benefits	BCR	Percent of Damages Reduced
PR1_Alt1	Small Beach Nourishment	9.5	20	10	-$1,415,000	0.43	57%
PR1_Alt2	Medium Beach Nourishment	9.5	20	25	-$1,332,000	0.53	80%
PR1_Alt3	Large Beach Nourishment	13	20	75	-$1,822,000	0.49	95%
PR1_Alt4	Small Beach Nourishment with ECS	9.5	20	10	-$934,000	0.57	66%
PR1_Alt5	Medium Beach Nourishment with ECS	9.5	20	25	-$821,000	0.68	92%
PR1_Alt6	Large Beach Nourishment with ECS	13	20	75	-$1,491,000	0.55	99%

The FWOP Beach-*fx* model runs indicated that little to no damages were expected in model reaches R035 to R039. The optimal placement area, based on the expected damages, in PR1 is from model reaches R028 to R034 (R-27 to R-34.5). This shoreline length of 1.4 miles is consistent with the most heavily filled areas of the current period of Federal participation. This area is just south of Bakers Haulover Inlet and is a known erosional area because of the inlet. While the area south of R-34.5 is not receiving any direct beach fill, it is expected that this area will receive some benefit from any beach nourishment project since the direction of net littoral drift in this area is from north to south. It should be noted that tapers are not included as part of the modeled fill and may extend several hundred feet beyond the physical limits covered by these model reaches.

6.6.1.2 Planning Reach 2 (PR2)

PR2 starts at the end of PR1 at R-39.3 and extends for 3.4 miles to R-56.5. A total of twelve Beach-*fx* alternatives were modeled for PR2. These alternatives include three different sized beach nourishment templates and the same beach nourishment templates with the presence of ECSs at known hotspots within PR2. It should be noted that while the beach nourishment template sizes are denoted as small, medium, and large, like the alternatives in PR1, the beach templates do not have the same dimensions as those in PR1. The beach nourishment templates chosen were based off the historical construction projects in the area (after considering project equilibration). The berms constructed in PR1 have historically been smaller than those in PR2. Additionally, the infrastructure in PR1 is generally set further behind the erosion control line (ECL) than in PR2, where infrastructure is often directly adjacent to the ECL. As a result, a larger series of berms was modeled for PR2. Table A-25 summarizes the twelve alternatives modeled for PR2.

The smallest beach nourishment template includes a dune crest elevation of 9.5 feet NAVD88, a dune crest width of 20 feet, and a berm width of 25 feet. The dune crest elevation of 9.5 feet NAVD88 and dune crest width of 20 feet are approximately equal to the existing dune elevation constructed as part of the existing Miami-Dade BEC&HP project. The berm width of 25 feet represents the minimum template that would likely be built for this planning reach. This beach nourishment template was used in Beach-*fx* models Alternative 1, Alternative 4, Alternative 7, and Alternative 10.

The medium beach nourishment template includes a dune crest elevation of 9.5 feet NAVD88, a dune crest width of 20 feet, and a berm width of 50 feet. This berm width was chosen because it was the middle width between the small and large templates. This beach nourishment template was used in Beach-*fx* models Alternative 2, Alternative 5, Alternative 8, and Alternative 11.

The large beach nourishment template includes a dune crest elevation of 13 feet NAVD88, a dune crest width of 20 feet, and berm width of 75 feet. This template represents the largest beach template that would likely be built for this planning reach. This beach nourishment template was used in Beach-*fx* models Alternative 3, Alternative 6, Alternative 9, and Alternative 12.

In addition to the three beach nourishment templates, ECSs were considered as an alternative in PR2. Structures such as groins and breakwaters can stabilize the shoreline and reduce nourishment rates and volumes needed in PR2. Within PR2, three erosional hotspots are known. These erosional hotspots are in the vicinity of model reaches R046, R050, and R055. Due to the proximity of the hotspots to each other and the net north to south littoral drift, any structural solutions considered for one hotspot would likely impact the other hotspots as well. ECSs were modeled in Beach-*fx* in conjunction with the three beach nourishment templates in Alternative 4 through Alternative 12.

Like in PR1, ECSs were modeled in PR2 in Beach-*fx* by changing the applied shoreline change rates within the model. For Alternative 4 through Alternative 6, the shoreline change rates were modified in model reaches R043 through R049 to simulate the presence of an ECS in R046. For Alternative 7 through Alternative 9, the shoreline change rates were modified in model reaches R043 through R054 to simulate the presence of an ECS at R046 and R050 combined. For Alternative 10 through Alternative 12, the shoreline change rates were modified in model reaches R043 through R059 to simulate the presence of an ECS at R046, R050, and R055. Note that if Alternative 10, 11, or 12 are selected for the TSP, the effects of the ECS at R055 would extend into PR3 and would need to be accounted for with the Beach-*fx* model for that area. Due to the proximity of these structures, the updrift and downdrift impacts of each ECS overlaps with the effects of the adjacent ECS. This creates a complex situation where a modification to one structure can resonate throughout the planning reach.

The types of ECS considered in PR2 were breakwaters (submerged, emergent, attached, and reefballs) and rubble mound groins. The AAEQ net benefit values shown in Table A-25 are reflective of costs which include reefball breakwaters at R046 as described in the Modeling Study of the Reefball Breakwater 227 Project (USACE 2014), submerged breakwaters at R050, as discussed in the 2006 Miami-Dade Morphological Change Study (CSI 2006), and submerged breakwaters at R055.

The FWOP Beach-*fx* model runs for PR2 indicated that damages were expected in all the model reaches. Due to these results, the optimum placement area for PR2 is the entire 3.4-mile shoreline length in PR2 (R-39.3 to R-56.5). It should be noted that tapers are not included as part of the modeled fill and may extend several hundred feet beyond the physical limits covered by these model reaches.

Table A-25. Planning Reach 2 Beach-*fx* Modeled Alternatives

Alternative	Description	Dune Crest Elevation (ft-NAVD88)	Dune Crest Width (ft)	Berm Width (ft)	AAEQ Net Benefits	BCR	Percent of Damages Reduced
PR2_Alt1	Small Beach Nourishment	9.5	20	25	-$1,753,000	0.53	80%
PR2_Alt2	Medium Beach Nourishment	9.5	20	50	-$1,954,000	0.54	92%
PR2_Alt3	Large Beach Nourishment	13	20	75	-$3,114,000	0.44	98%
PR2_Alt4	Small Beach Nourishment with ECS at model reach R046	9.5	20	25	-$2,712,000	0.43	81%
PR2_Alt5	Medium Beach Nourishment with ECS at model reach R046	9.5	20	50	-$2,431,000	0.48	91%
PR2_Alt6	Large Beach Nourishment with ECS at model reach R046	13	20	75	-$2,674,000	0.44	86%
PR2_Alt7	Small Beach Nourishment with ECS at model reaches R046 and R050	9.5	20	25	-$2,675,000	0.43	82%
PR2_Alt8	Medium Beach Nourishment with ECS at model reaches R046 and R050	9.5	20	50	-$2,449,000	0.48	92%
PR2_Alt9	Large Beach Nourishment with ECS at model reaches R046 and R050	13	20	75	-$2,634,000	0.47	95%
PR2_Alt10	Small Beach Nourishment with ECS at model reaches R046, R050, and R055	9.5	20	25	-$2,376,000	0.47	83%
PR2_Alt11	Medium Beach Nourishment with ECS at model reaches R046, R050, and R055	9.5	20	50	-$2,572,000	0.47	93%
PR2_Alt12	Large Beach Nourishment with ECS at model reaches R046, R050, and R055	13	20	75	-$2,668,000	0.47	94%

6.6.1.3 Planning Reach 3 (PR3)

PR3 extends from R-56.5 to the north jetty of Government Cut at R-74 (3.5 miles). A total of two Beach-*fx* alternatives were modeled for PR3. Both alternatives include a modification to the existing breakwaters at 32nd Street. In addition to modifications of the existing breakwaters, the first alternative also includes adding additional ECSs to stabilize an existing hotspot at R-61. The second alternative includes beach nourishment in addition to modification of the existing breakwaters. Table A-26 summarizes the two alternatives modeled for PR3. It should be noted that the magnitude of damages seen in the FWOP model runs in this area was significantly less than those seen in the other planning reaches which made a beach-nourishment-only alternative in this location unlikely to be economically justified due to the cost of the sand.

The three existing 32nd Street attached rubble-mound breakwaters were built in 2002 to stabilize an existing erosion hotspot at R-59. These structures were effective at stabilizing the shoreline and alleviating the existing erosional hotspot but created a new hotspot to the south of the structures (R-60 to R-61) due to a sediment flux deficit. The existing structures trap material and prevent longshore sediment transport from the north, creating a downdrift sand deficit. Material can flow around the structures in an offshore sandbar, but this sandbar only reattaches itself to the beach near R-63. This creates a 2,000-to 3,000-foot stretch of shoreline with a sediment influx deficiency.

One approach to stabilize this area includes modifications to the existing structures to reduce their effectiveness at trapping material. By increasing the permeability of the structures or moving them further offshore, the structures can still perform their original task of stabilizing the beach at R-59 while allowing more sand to flow to the resulting hotpot between R-60 and R-61. Leaving the structures as-is is not recommended at this location because the high erosion rates from R-60 to R-61 necessitate a high frequency of repeated renourishments in this area. Modifications to the existing structures were included in both Alternative 1 and Alternative 2.

In Alternative 1, the modifications to the existing breakwaters were modeled. Additionally, a series of new ECSs were also modeled. These structures would extend to the south until approximately R-63. The shoreline south of R-61 is gradually less erosional and eventually becomes accretional near R-64. The new structures would extend to the south to tie the erosional areas into the accretional portion of the beach. Extending the new structures to an accretional portion of the beach allows for the naturally accretional shoreline to absorb any downdrift impacts of the new structures and reduces the risk of creating another erosional hotspot to the south. Additional refinements to reduce structure-end effects (reduced height/length, or increased gap width or offshore position) would occur during the detailed design phase.

Like in PR1 and PR2, ECSs (and modifications to the existing breakwaters) were modeled in PR3 in Beach-*fx* by changing the applied shoreline change rates within the model. For Alternative 1, the shoreline change rates of model reaches R057 through R068 were modified to reflect the updrift and downdrift impacts of modifying the existing breakwaters and adding an additional ECS. The BCR values in Table A-26 are reflective of costs which include moving the existing breakwaters offshore and building four additional breakwaters to the south of the existing ones. Section 7.6 discusses a preliminary design of the breakwaters.

In Alternative 2, in addition to modifications to the existing emergent breakwaters, beach nourishment was also included in the model. The beach nourishment template includes a dune crest elevation of 9.5 feet NAVD88, a dune crest width of 20 feet, and berm width of 50 feet. The dune crest elevation of 9.5 feet NAVD88 and dune crest width of 20 feet are approximately equal to the existing dune elevation constructed as part of the existing Miami-Dade BEC&HP project. The berm width of 50 feet represents the typical beach template constructed in this vicinity under the existing BEC&HP project.

The shoreline change rates were also modified in Alternative 2 to reflect the modifications to the existing structures by moving them further offshore. The modifications were made for model reaches R057 through R063. The FWOP Beach-*fx* model runs for PR3 indicated that little to no damages were expected south of model reach R063. Based on the expected damages, the optimal placement area for any beach nourishment would be from R060 to R063 (R-60 to R-63.5). It should be noted that tapers are not included as part of the modeled fill and may extend several hundred feet beyond the physical limits covered by these model reaches. The details of the economic damages can be seen in Appendix B: Economics.

The area south of R-64 is being considered as a borrow area for the erosional areas in this study. This area has accumulated large amounts of beach quality material due to the net north to south littoral drift for the Main Segment. Much of the material placed during beach nourishments for the existing Miami-Dade BEC&HP project has accumulated in this area during the project life. Back-passed material from this area can be used to periodically fill erosional areas within the Main Segment at a low cost compared to upland mines and further offshore sand sources.

Table A-26. Planning Reach 3 Beach-*fx* Modeled Alternatives

Alternative	Description	Dune Crest Elevation (ft-NAVD88)	Dune Crest Width (ft)	Berm Width (ft)	AAEQ Net Benefits	BCR	Percent of Damages Reduced
PR3_Alt1	Modification of existing breakwaters plus construction of additional ECS	N/A	N/A	N/A	-$207,000	0.51	97%
PR3_Alt2	Modification of existing breakwaters plus beach nourishment	9.5	20	50	-$1,178,000	0.12	75%

6.6.2 KEY BISCAYNE SEGMENT ALTERNATIVES

6.6.2.1 Planning Reach 4 (PR4)

PR4 is the only planning reach located on Key Biscayne. PR4 extends from R-101.3 to R-108 (1.2 miles) which is the only portion of the island with significant amounts of infrastructure. North of R-101.3 is Crandon Park and south of R-108 is Bill Baggs Cape Florida State Park. A total of six Beach-*fx* alternatives were modeled for PR4. These alternatives include three different size beach nourishment templates, ECSs, and a coastal dune with reinforced core. It should be noted that while the beach nourishment template sizes are denoted as small and large, like the alternatives in PR1 and PR2, the beach templates do not have the same dimensions as those in PR1 and PR2. Table A-27 summarizes the six alternatives modeled for PR4.

The small beach nourishment template includes a dune crest elevation of 9 feet NAVD88, a dune crest width of 40 feet, and a berm width of 30 feet. The dune crest elevation of 9 feet NAVD88 and 40-foot dune crest width are approximately equal to the existing natural dune in the project area. The berm width of 30 feet and dune elevation of 9 feet NAVD88 represent the minimum template that would likely be maintained for this planning reach and is approximately equal to average existing project conditions based on surveys between 2016 and 2019. This beach nourishment template would have both direct and indirect impacts to seagrass which requires mitigation. This beach nourishment template was used in Beach-*fx* models Alternative 1 and Alternative 4.

The large beach nourishment template includes a dune crest at 11 feet NAVD88, a dune crest width of 60 feet, and a berm width of 60 feet. This template represents the largest beach template that would likely be built for this planning reach. This beach nourishment template would have both direct and indirect impacts to seagrass which requires mitigation. This beach nourishment template was used in Beach-*fx* models Alternative 2 and Alternative 5.

The no-impact beach nourishment template includes a dune crest elevation of 11 feet NAVD88, a dune crest width of 15 feet, and a berm width of 5 feet. This beach nourishment template is designed to avoid/minimize potential impacts to seagrass. This beach nourishment template was used in Beach-*fx* model Alternative 6.

In addition to the three beach nourishment templates, ECSs were considered as an alternative in PR4. Structures such as groins and breakwaters can stabilize the shoreline and reduce nourishment rates and volumes needed in PR4. In PR4 the sediment pattern is erosion that radiates from the center of the Key Biscayne Segment (R-104 to R-105) and causes sediment to flow to the north and south. Based on the proximity of nearshore seagrasses, a series of groins would likely be chosen over breakwaters to minimize impacts to environmental resources. Additionally, a series of groins have been effective in neighboring Virginia Key. ECSs were modeled by themselves in Beach-*fx* Alternative 3 and then modeled in conjunction with the small and large beach nourishment templates in Alternative 4 and Alternative 5.

Alternative 6 includes a minimal beach nourishment template (5 feet) with a coastal dune with a reinforced core. A coastal dune with a reinforced core is a hybrid shore protection feature that includes both hard structures and natural landforms. The advantage of a dune with a reinforced core is that even if the berm and natural dune are eroded during a storm, the reinforced dune core will still be present and can prevent inundation damages. One benefit of a dune with a reinforced core is that it can potentially allow for a smaller beach berm in front of it with similar benefits. This can reduce the impacts to environmental resources in the project area compared to a traditional beach template.

The FWOP Beach-*fx* model runs for PR4 indicated that damages were concentrated in model reach R104 due to the concentration of high value, slab-on-grade, single-family residences that were extremely susceptible to inundation damage. It should be noted that tapers are not included as part of the modeled fill and may extend several hundred feet beyond the physical limits covered by these model reaches.

Table A-27. Planning Reach 4 Beach-*fx* Modeled Alternatives

Alternative	Description	Dune Crest Elevation (ft-NAVD88)	Dune Crest Width (ft)	Berm Width (ft)	AAEQ Net Benefits	BCR	Percent of Damages Reduced
PR4_Alt1	Small Beach Nourishment	9	40	30	-$841,000	0.60	7%
PR4_Alt2	Large Beach Nourishment	11	60	60	$2,961,000	1.78	36%
PR4_Alt3	ECS without Beach Nourishment	N/A	N/A	N/A	-$52,000	0.93	3%
PR4_Alt4	Small Beach Nourishment with ECS	9	40	30	-$911,000	0.53	6%
PR4_Alt5	Large Beach Nourishment with ECS	11	60	60	$2,827,000	1.72	36%
PR4_Alt6	Coastal Dune with Reinforced Core and No Impact Beach Nourishment	11	15	5	$5,518,000	3.59	41%

6.7 RECOMMENDATION FOR TENTATIVELY SELECTED PLAN

The Main Segment was broken down into three planning reaches (PR1, PR2, and PR3) for the Beach-*fx* modeling but will be combined to form one comprehensive tentatively selected plan (TSP). Key Biscayne (PR4) will have its own TSP because of the physical separation between Key Biscayne and the Main Segment.

6.7.1 MAIN SEGMENT TENTATIVELY SELECTED PLAN

Screening of the project alternatives using the Beach-*fx* model for the Main Segment PR1 identified Alternative 5 (PR1_Alt5) as the TSP because it provided the highest net benefits. Alternative 5 includes a protective dune with a crest elevation at 9.5 feet NAVD88, a 20-foot-wide dune crest, and a 25-foot-wide berm extending from R-27 to R-34.5 (1.4 miles). The beach fill also includes a taper extending approximately 2,000 feet to the south to R-36.5. Alternative 5 also includes ECSs between R-28 and R-31.5, which is the area with the highest erosion rates.

While both breakwaters and groins could be used to reduce erosion in this area, groins were selected for the TSP. Groins were selected because of the proximity of the Baker's Haulover Inlet ebb shoal. The ebb shoal provides a protective buffer against large waves reaching the Bal Harbour shoreline and adding breakwaters offshore in this area has the risk of causing unforeseen changes to the behavior of the ebb shoal. The ebb shoal also provides a pathway for natural transport of sediment around the inlet. Groins can provide the same amount of erosion reduction in the project area with less risk of adversely affecting the ebb shoal.

The preliminary groin design for the TSP was based off the design described in the 2003 Dade County, Florida Beach Erosion Control and Hurricane Protection Project Bal Harbour Design Memorandum (USACE 2003). The TSP design includes a total of five groins with granite armor stone with lengths ranging from 60 feet to 220 feet long and a total combined structure length of 915 feet. The preliminary design includes T-heads for the northernmost two groins, with the lengths of the structures tapered to the south (Table A-28). Final design of the groins should be further evaluated prior to construction during the Preliminary Design and Engineering (PED) phase using a more sophisticated modeling and analysis to determine optimum groin field configuration.

Table A-28. Lengths of Bal Harbour Groins for TSP

Structure	Approximate Location	Structure Length (ft)
Groin 1	R-28	220 (295)*
Groin 2	R-29	190 (240)*
Groin 3	R-29.8	200
Groin 4	R-30.5	120
Groin 5	R-31.3	60

*Includes perpendicular lengths of T-head

No beach fill is recommended between R-34.5 and R-39.5 because the FWOP Beach-*fx* model runs indicate little to no damage is expected in this area. While this area is not receiving any direct beach fill, it is expected that this area will receive some benefit from any beach nourishment project in Bal Harbour since the direction of net littoral drift in this area is from north to south.

Screening of the project alternatives using the Beach-*fx* model for the Main Segment PR2 identified Alternative 1 (PR2_Alt1) as the TSP because it had a nearly equivalent BCR with Alternative 2 but had higher net benefits, making it the National Economic Development (NED) plan. Alternative 1 includes a protective dune with a crest elevation at 9.5 feet NAVD88, a 20-foot-wide dune crest, and a berm width of 25 feet extending from R-39.5 to R-56.5 (3.4 miles). The beach fill also includes 1,000 feet tapers to the north (R-38.5) and the south (R-57.5).

Screening of the project alternatives using the Beach-*fx* model for the Main Segment did not identify any feasible project features within PR3. Alternative 1 (PR3_Alt1) has a BCR greater than 0.5 considering only storm damage reduction benefits but no additional NED or incidental recreation benefits have been identified in this planning reach. Because no additional benefits have been identified to raise the BCR above a 1.0, the no-action alternative is recommended for the TSP in this reach. The alternative with the highest BCR was Alternative 1, which includes modification of the existing 32nd Street breakwaters and the addition of new ECSs extending from R-60 to R-63.

One concern with not having a justified project in PR3 is that the erosional hotspot at R-61 could continue to erode and cause armor to be placed along this shoreline. If armor is constructed in this area, it will likely increase erosion to the adjacent shoreline. The downdrift beaches in Miami South Beach (R-65 to R-74) are being considered as a borrow area for PR2 but increases in erosion due to the construction of armor could increase the erosion in this area. This will need to be further evaluated to determine whether this could impact the amount of volume available from the proposed borrow area and whether project damages in this area would increase.

No CSRM measures are recommended south of R-63. South Miami Beach (R-65 to R-74) becomes increasingly accretional to the south. This area is being considered a borrow area for material in the rest of the project. Material would be back-passed via truck haul or dredge to erosional areas within the Main Segment.

A summary of the TSP for the Main Segment can be seen in Table A-29.

Table A-29. Summary of TSP for Main Segment

Location	Measure	Dune Crest Elevation (ft-NAVD88)	Dune Crest Width (ft)	Berm Width (ft)	Total Structure Length (ft)
R-27 to R-34.5	Beach Fill & Dune	9.5	20	25	-
R-28 to R-31	Groin Construction	-	-	-	915
R-34.5 to R-39.5	None	-	-	-	-
R-39.5 to R-56.5	Beach Fill & Dune	9.5	20	25	-
R-56.5 to R-63	None	-	-	-	-
R-63 to R-74	Borrow Area	-	-	-	-

6.7.2 KEY BISCAYNE TENTATIVELY SELECTED PLAN

Screening of the project alternatives using the Beach-*fx* model for Key Biscayne (PR4) identified Alternative 6 (PR4_Alt6) as the TSP because it provided the highest BCR. Alternative 6 includes a protective dune with a crest elevation at 11 feet NAVD88, a 15-foot-wide dune crest, and a 5-foot-wide berm extending along the shoreline from R-101.3 to R-108 (1.2 miles). The beach fill also includes tapers extending approximately 1,000 feet to the north to R-100.3 and 1,000 feet to the south to R-109. Alternative 6 also includes a reinforced dune. The reinforced dune includes a sheet pile seawall that is entirely contained within the core of the dune. The predominant source of damage in this study area is due to inundation. This seawall within the dune will provide inundation protection even if the dune is damaged and eroded. The seawall elevation is at 11 feet NAVD88 based on the water levels seen in the Beach-*fx* model. It is believed that this elevation will protect the project area from most damages. The seawall will tie-back to Crandon Blvd. on both the north and south sides of the project area. The total structure length is approximately 9,060 feet. This length includes 6,560 feet of wall along the shoreline, a tie-back of 1,800 feet in the north, and a tie-back of 700 feet in the south. This alternative will provide protection from inundation on the oceanside but will not provide any protection from back bay flooding. Local efforts will need to be pursued to guarantee that the project benefits will not be impacted by back bay flooding. A summary of the TSP for the Main Segment can be seen in Table A-30.

Table A-30. Summary of TSP for Key Biscayne Segment

Location	Measure	Dune Crest Elevation (ft-NAVD88)	Dune Crest Width (ft)	Berm Width (ft)	Total Structure Length (ft)
R-101.3 to R-108	Beach Fill & Reinforced Dune (Seawall)	11	15	5	9,060

6.7.3 PROJECT OPTIMIZATION

Between the tentatively selected plan milestone and agency decision milestone, the PDT will work to optimize the TSP. For the Main Segment, possible optimizations include optimization of the project fill lengths and combining PR1 and PR2 beach nourishments to save on construction mobilization costs. Verification of the sand source volumes and optimization of the order in which the sand sources are used for the nourishment events will also occur.

The optimization of the Key Biscayne Segment will verify that the seawall dimensions described in the TSP cannot be further modified to improve project performance or reduce project costs.

7 PROJECT DESIGN

The project design includes beach fill and ECSs along portions of the Miami-Dade Main Segment and Key Biscayne shorelines as described in the following sections.

7.1 PROJECT LENGTH

Project evaluation occurred along the 9.3 miles of the Miami-Dade Main Segment (R-27 to R-74) and the 4.1 miles of ocean-facing shoreline of Key Biscayne (R-92 to R-113).

Based on the project evaluation, the Main Segment will receive beach nourishment along two stretches of shoreline under the TSP. The Village of Bal Harbour and the Town of Surfside will receive beach fill from R-27 to R-34.5 (1.4 miles), and north Miami Beach will receive beach fill from R-39.5 to R-56.5 (3.4 miles) for a total beach fill length of 4.8 miles. Additionally, the TSP includes the addition of groins from R-28 to R-31.

The areas from R-34.5 to R-39.5 and from R-56.5 to R-63 do not include any project recommendations but are expected to receive continued indirect benefits from sand placements to the north due to the net sediment transport of north to south. The area from R-63 to R-74 is generally accretional as material is trapped by the Government Cut north jetty. As part of the TSP, this area does not have any coastal storm risk management measures recommended. Instead, this area will be used as a borrow area for the Main Segment areas to receive beach fill.

Based on the project evaluation, Key Biscayne will receive minimal beach nourishment at the Village of Key Biscayne from R-101.3 to R-108 (1.2 miles). Additionally, the TSP includes a reinforced dune which contains a buried seawall along the project length.

7.2 PROJECT BASELINE

The project baseline is the line that is used as a reference for the location of the project beach fills. The project baseline for the Main Segment will be the FDEP erosion control line. The project baseline for Key Biscayne will be established during PED based on the position of the seawall. The seawall will be placed as landward as possible while avoiding impacts to the existing infrastructure as practical.

7.3 PROJECT CROSS-SHORE DIMENSIONS

The cross-shore dimensions of the beach fills for the project design can be described by three factors: the dimensions of the dune, dimensions of the berm, and shoreline slopes. These project dimensions are described in the following sections. It should be noted that while specific project cross-shore dimensions are given in the following sections, the level of protection generally correlates more to the volume of material rather than the specific geometric shape of the beach. As such, it can be assumed that some variations to the cross-shore dimensions can still result in the same level of protection in many cases if the appropriate volume is placed. For example, this could involve building a smaller berm width but placing larger quantities of material at a higher berm elevation or in the dune system.

7.3.1 PROJECT DUNE

The TSP for the Main Segment includes a project dune with a dune crest elevation of 9.5 feet NAVD88 and dune crest width of 20 feet for the areas from R-27 to R-34.5 and R-39.5 to R-56.5. These are approximately the same dimensions of the dune in the existing Miami-Dade BEC&HP project. The existing dune in the Main Segment is typically larger than the TSP dune. The existing dune is generally at an elevation of 10 to 11 feet NAVD88 with widths from 40 to 80 feet. Evaluation of the design alternatives has shown that the designed elevations, when combined with berm extension, provide sufficient protection in most locations. Additional dune elevation may be needed in the vicinity of R-28 to R-31, but it is recommended that any minor modifications to the existing dunes be done when the existing dune is damaged to avoid damaging the existing dune vegetation unless the existing dune is deemed to be immediately vulnerable during project construction.

The TSP for Key Biscayne includes a project berm width of 5 feet and a project dune with a dune crest elevation of 11 feet NAVD88 and dune crest width of 15 feet from R-101.3 to R-108. The existing dune in Key Biscayne is generally smaller than the TSP dune with crest elevations of 8 to 9 feet NAVD88 and crest widths of 40 feet. In addition, the TSP for Key Biscayne includes a reinforced dune that contains a buried seawall. The seawall will be at elevation 11 feet NAVD88. The seawall will typically be buried within the dune and will protect against inundation if the dune is damaged or eroded. Ideally, the wall should be buried a few feet under the dune crest elevation to allow for vegetation to be rooted and avoid the safety hazard of the top of the wall being exposed. As a result, additional elevation of the dune crest may be needed.

The cross-shore dune dimensions for the Main Segment and Key Biscayne model reaches that are part of the TSP are summarized in Table A-31 to compare the existing conditions of the dunes in each model reach to the TSP. These are the minimum dune dimensions required during a nourishment in the Beach-*fx* model. Any erosion of material from the existing idealized dune template is replaced during nourishments in model simulations. The project dune is an important feature of the CSRM project and will be restored or constructed as necessary during initial construction and renourishment.

Table A-31. Existing and TSP Cross-shore Dune Dimensions

Idealized Profile	Model Reach	Upland Elevation (ft-NAVD88)	Existing Dune			TSP Dune			
			Elevation (ft-NAVD88)	Height Above Berm (ft)	Width (ft)	Elevation (ft-NAVD88)	Height Above Berm (ft)	Width (ft)	Dune Slope (V:H)
MD01	R028, R031 R032, R033 R034, R039 R040, R041 R042, R043 R044, R045 R046, R050 R051, R052	4	11	7	60	9.5	5.5	20	1:5
MD02	R029 R030	6	9	3	60	9.5	3.5	20	1:5
MD03	R047 R048	7	10	3	30	9.5	2.5	20	1:5
MD04	R049 R053 R054	6	10	4	70	9.5	3.5	20	1:5
MD05	R055 R056	5	10	5	40	9.5	4.5	20	1:5
KB01	R102	4	9	5	40	11	7	15	1:3
KB02	R104 R106 R107	4	8	4	40	11	7	15	1:3

7.3.2 PROJECT BERM

The design berm elevation for the Main Segment beach fill areas varies for each beach fill area based on the natural berm elevation. Restricting the design berm elevation to the natural berm elevation minimizes scarping of the beach fill as it undergoes profile equilibration. Vertical scarps can hinder beach access by nesting sea turtles and may also pose safety problems for recreational beach use. Other reasons for following the natural berm elevation are related to storm damage protection. A berm constructed at a lower elevation would increase the probability of overtopping by relatively frequent storms, thereby offering less protection to upland development and/or existing dunes. A higher berm elevation could result in problems related to backshore flooding due to excessive rainfall or wave overtopping. A higher berm may also be more susceptible to wind-induced erosion.

The berm elevation for the Main Segment beach fill areas (R-27 to R-34.5 and R-39.5 to R-56.5) is 7 feet NAVD88. The berm elevation for Key Biscayne is 4 feet NAVD88 for the beach fill area from R-101.3 to R-103 and 3 feet NAVD88 from R-103 to R-108.

The TSP berm width for the Bal Harbour and Surfside beach fill area from R-27 to R-34.5, based on the Beach-*fx* analysis, is 25 feet. The berm width for the north Miami Beach fill area from R-39.5 to R-56.5 is 25 feet. The berm width for the Key Biscayne fill area from R-101.3 to R-108 is 5 feet. Construction of the recommended plan alternative will include a berm that is wider than what was modeled to account for the additional material below the 0 feet-NAVD88 contour and the difference in idealized/modeled slope versus practical construction slopes. Following construction and equilibration of the profile, the beach dimensions are expected to approximate the idealized profile. The TSP berm dimensions in **Table A-32** reflect equilibrated conditions and construction widths are discussed in **Section 7.7**.

Table A-32. Existing and TSP Cross-shore Berm Dimensions

Location	R-Monuments	Existing Berm		TSP Berm	
		Elevation (ft-NAVD88)	Width (ft)	Elevation (ft-NAVD88)	Width (ft)
Bal Harbour/Surfside	R-27 to R-34.5	7	30-40	7	25
North Miami Beach	R-39.5 to R-56.5	7	30-170	7	25
Key Biscayne	R-101.3 to R-103	4	40	4	5
Key Biscayne	R-103 to R-108	3	10	3	5

7.3.3 PROJECT BEACH SLOPES

After adjustment and sorting of the placed material by wave action, the material is expected to adjust to an equilibrium beach slope, like the native beach. In the Main Segment of Miami-Dade County, the native beach slopes in the project area are approximately 1 foot Vertical to 5 feet Horizontal (V:H) at the dune, 1V:8H from the berm to MLW (approximately -2.11 feet-NAVD88), and 1H:55H below MLW. In the Key Biscayne Segment, the native beach slopes are approximately 1V:4H at the dune, 1H:10H from the berm to MLW (approximately -1.88 feet-NAVD88), and 1H:100V below MLW. The estimate of the slope of the material after adjustment is based on averaging the beach profile slopes of the native beach from the MLW datum to the approximate location of the 15-foot depth contour. Sand from the project borrow sites (see Section 0:

Borrow Areas) was determined to be a near match to the gradation and shell content of the existing beach. This will allow the beach fill to equilibrate to a shape like the existing profile. For more details about the sand characteristics of the beach and borrow areas, see Appendix C: Geotechnical.

It is unnecessary and impractical to artificially grade beach slopes below the low water elevation since they will be shaped by wave action. For this reason, the front slope of the beach fill placed at the time of construction or future renourishment may differ from that of the natural profile. The angle of repose of the placed material depends on the characteristics of the fill material and the wave climate in the project area. With steep initial slopes, the material will quickly adjust to the natural slopes. For design purposes, it is assumed that that construction berm will have an approximate slope of 1:10.

7.4 PROJECT VOLUMES AND RENOURISHMENT INTERVAL

Each complete Beach-*fx* model run consists of 50 iterations, each iteration representing the life of the project (50 years). From the multi-iteration lifecycle modeling, a range of volumes was determined for the initial fill event and each subsequent renourishment event for all the areas that received beach nourishment. Model runs were made for the high sea level rise scenario. To maintain compliance with ER 1100-2-8162, the recommended plan will be checked against the intermediate and low SLC curves to ensure the project still provides net benefits under those scenarios. Table A-33 provides average fill volumes (for both initial and renourishment events) and renourishment intervals over the life of the project for the TSP. Final optimization of the TSP may include variable berm widths between the project segments.

Table A-33. Project Volumes for Miami-Dade County TSP Berm

Project Area	Sea Level Change Case	Initial Construction Year	Initial Fill Volume (cubic yards)	Renourishment Interval (years)	Average Volume per Interval (cubic yards)
Bal Harbour/Surfside R-27 to R-34.5	High	2026 (groins) 2035 (beach fill)	247,000	4	289,500
North Miami Beach R-39.5 to R-56.5	High	2035 (beach fill)	386,500	4	564,600
Key Biscayne R-101.3 to R-108	High	2026 (seawall) 2029 (beach fill)	26,200	2	24,500

7.5 BORROW AREAS

Four sources of material are expected to be used for the TSP. The first source of material is from upland mines that can use trucks to transport material to the project area. This is the expected source material for the Key Biscayne Segment due to the relatively low fill volume. This is the sand source that has been used during past nourishments of the project. There is no limit to the volume of sand that can be obtained from this sand source. Details on specific mines approved for this area can be found in Appendix C: Geotechnical.

The second borrow area is the Baker's Haulover Inlet Ebb shoal. The Baker's Haulover north jetty prevents sand from by-passing the inlet, causing a deficit of material to the Bal Harbour shoreline to the south of the inlet. Most of this material becomes trapped in the inlet complex and is available to be dredged. The shoal complex (flood and ebb shoals) has been used to nourish Bal Harbour in the past. The ebb shoal is the expected primary source of sand for the Bal Harbour and Surfside project area for the TSP. This is the ideal source of material for this project segment because it is material that would naturally drift from Haulover Beach Park if not trapped by the ebb shoal. It is expected that an average of 36,800 cy/yr can be obtained from the ebb shoal, for a total volume over the project life of 1,840,000 cy.

The third borrow area is Lummus Park from approximately R-64 to R-74. The shoreline has been accretional in this area since initial construction was completed in 1982. The Government Cut north jetty has trapped a significant amount of material in this area. It is estimated that an average of 50,000 cy of material shoals per year (USACE 2016), and that approximately 900,000 cy of material is available in the nearshore at this time. This would allow for a total volume of 3,300,000 cy to be dredged from this source over the 50-year project life. These volume estimates assume a maintained minimum berm width of 200 feet on Lummus Park and used the -15 feet NAVD88 contour as the offshore boundary. The material is expected to be obtained via dredging of the nearshore. This borrow area is expected to be used as the primary source of material for the North Miami Beach fill area. Back-passing this material is ideal because it allows the same material to be reused multiple times over the project life rather than needing to locate new sources of sand.

The final borrow area is a series of offshore borrow areas identified in the USACE South Atlantic Division Sand Availability and Needs Determination Report (Taylor 2020). These borrow areas are expected to contain a total of 6,600,000 cy and are to be used as secondary sources for both the Bal Harbour and Surfside and the North Miami Beach nourishment projects. Details of these borrow areas can be found in Appendix C: Geotechnical.

7.6 PROJECT STRUCTURES

The TSP for the Miami-Dade CSRM project includes structures at two locations within the project area. The northernmost structures are a series of five rubble mound groins located in Bal Harbour between R-28 and R-31.3. These groins are spaced approximately 800 feet apart and the lengths taper to the south. See Table A-28 for the lengths of the groins. The two northernmost structures have T-heads included to increase the structures' effectiveness at trapping material. The size of the groins was based off the cross-sectional dimensions (width and height) of the submerged breakwaters located in Sunny Isles, located approximately 10 miles to the north of the project area. The groin design includes a height of 8.4 feet, side slopes of 1V:1.5H feet, a crest width of 12.5 feet, and bottom width of approximately 37 feet (bottom width will depend on existing topographic grade). The groins will also require a marine mattress for stability and a scour protection. The lengths of the groins for the preliminary design are found in Table A-28 (Section 6.7.1). This design is likely an overestimation of the size of the structure needed at this location. Final structure sizes and dimensions will be determined using more sophisticated modeling and analysis during PED. The cross-section of the Sunny Isles breakwaters used in the design is shown in Figure A-33.

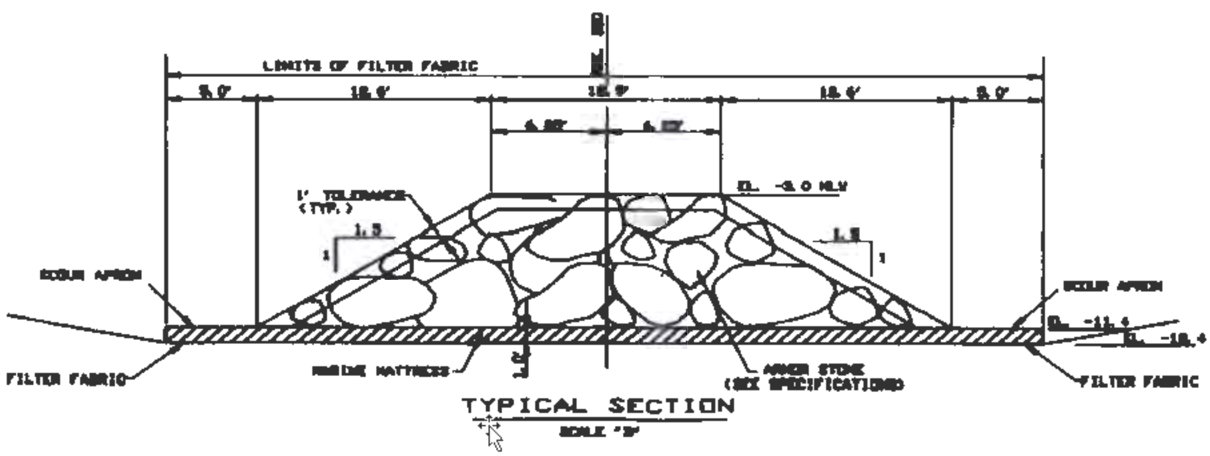


Figure A-33. Cross-section of Sunny Isles Breakwaters

The second structure in the TSP is the reinforced dune core in Key Biscayne. This design includes a steel sheet pile seawall with a concrete cap that is buried under a sand dune. The dune and beach berm provide protection for the seawall from erosion and wave impacts, and the seawall provides protection from inundation damage for the project area. Ideally the wall should be buried a few feet under the dune crest elevation to allow for vegetation to be rooted and avoid the safety hazard of the top of the wall being exposed. The preliminary design for the wall includes a total length of 6,560 feet. This seawall protects the shoreline between R-

101.3 and R-108 (4,060 feet) and includes tiebacks to the north (1,800 feet) and south (700 feet) to Crandon Blvd, which is the main road that bisects Key Biscayne. These tieback lengths are conservative, and the actual lengths needed may be shorter depending on the location of existing high ground. The seawall only protects against inundation damage from the oceanside, but damage to the project area can still be caused by flooding from the back bay side of the island due to the low elevations of Key Biscayne. It is assumed that other efforts by the non-Federal sponsor will address the residual risk from back bay flooding. The preliminary design of the seawall is based on a size NZ-14 steel sheet pile, which has a crest elevation of 11 feet NAVD88 and extends into the ground to -15 feet NAVD88. The design also includes either a concrete sheet pile cover or coal tar epoxy protective layer to prevent corrosion. A Qualitative Risk Assessment will be completed on the wall between TSP and the Agency Decision Milestone per risk-based guidance ER 1105-2-101 (USACE 2019c) and ECB 2019-15 (USACE 2019d). A typical cross-section of the seawall and beach fill configuration is shown in Figure A-34.

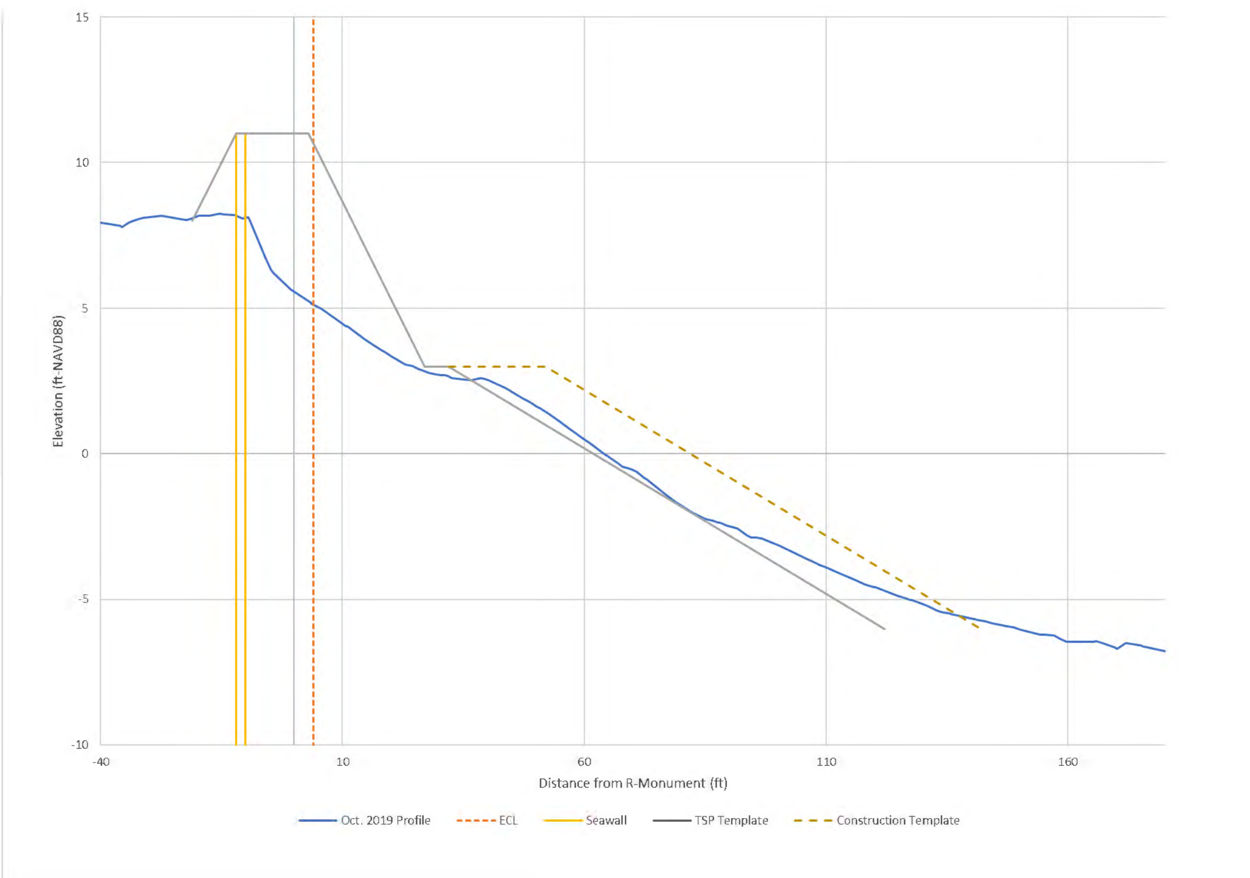


Figure A-34. Typical Cross-section of Key Biscayne Seawall

7.7 PROJECT CONSTRUCTION

As previously discussed, the front slope of the beach fill placed at the time of construction or future renourishment may differ from that of the natural profile. This reflects the capabilities of the construction equipment that will be used to build the shore protection project. Within the first year or two after placement of the beach fill, the construction profile will be reshaped by waves into an equilibrium profile, causing the berm to retreat to a position more characteristic of the project design template.

Based on the approximated initial fill volume and constructability considerations, a construction template applicable to the TSP equilibrated berm for all the beach fill areas was determined. Table A-34 shows the construction berm widths for each of the beach fill areas. The construction templates will equilibrate into the project template. The volume of material in the equilibrated profile (between the template and the "existing" condition) represents the material that is expected to erode between successive nourishment events including portions of the dune. Figure A-35 shows a conceptual cross-shore profile and construction berm of the Main Segment and Figure A-36 shows a conceptual cross-shore profile and construction berm of the Key Biscayne Segment.

Table A-34. Approximate TSP Construction Template Berm Widths

Fill Segment	Segment Length (ft)	TSP Berm Width (ft)	Construction Fill Volume (cy)	Construction Fill Density (cy/lf)	Construction Fill Berm Width (ft)
R-27 to R-34.5	7,800	25	289,400	37	75
R-39.5 to R-56.5	18,100	25	564,600	31	65
R-101.3 to R-108	6,500	5	24,500	4	20

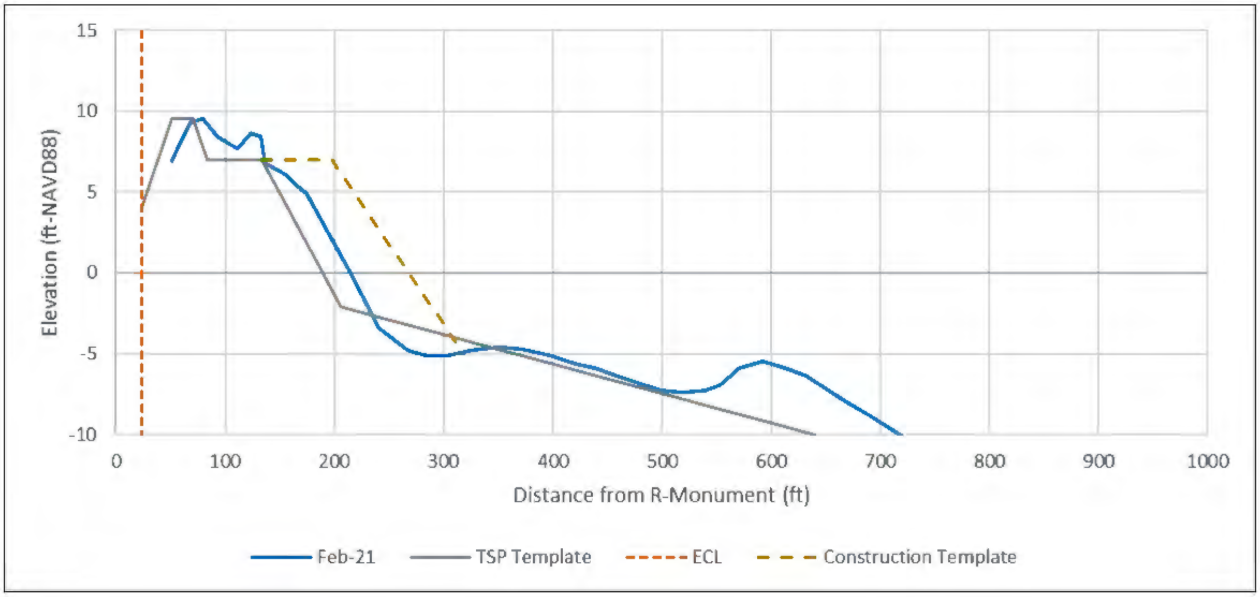


Figure A-35. Conceptual Cross-shore Profile and Construction Berm for Main Segment TSP

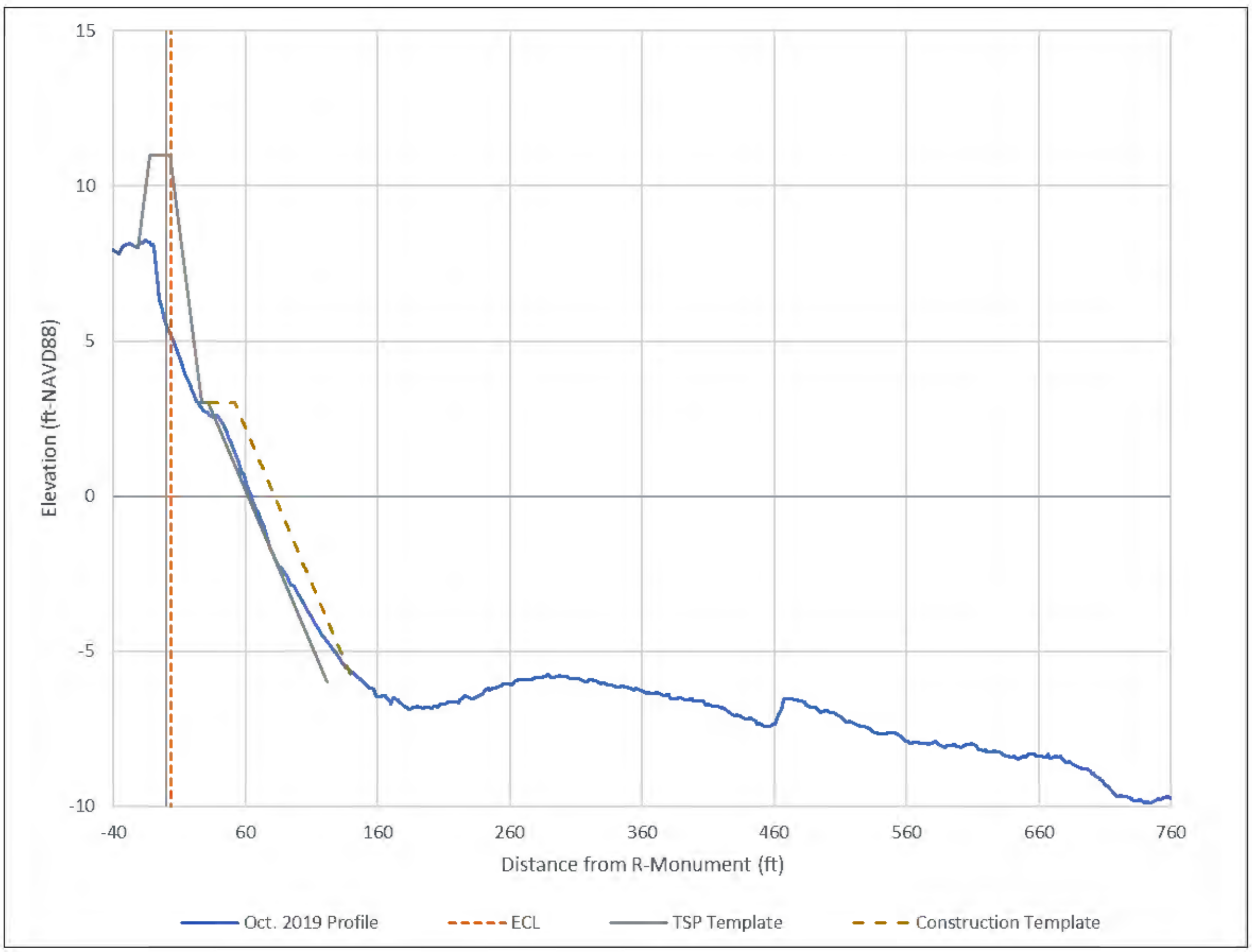


Figure A-36. Conceptual Cross-shore Profile and Construction Berm for Key Biscayne Segment TSP

Other considerations during project construction include the removal of the existing groins in Bal Harbour, potential seagrass impacts and mitigation for Key Biscayne, and potential hardbottom impacts in south Miami Beach.

In Bal Harbour, a series of five decrepit king pile groins is in the same locations as the proposed groin construction in the TSP. It is likely that the removal of the king piles and any other remnants of the structures is necessary before the construction of the new structures. In addition, it may be necessary to backfill the structures during construction to help the shoreline to equilibrate faster. This will depend on the condition of the beach during construction.

Seagrass impacts are a concern with the TSP for Key Biscayne. Any impacts to seagrass will require mitigation. The seagrass is thick in this area and there are limited available locations for mitigations, so limiting impacts to the seagrass is important during construction in this area. This project is expected to be constructed using truck haul instead of a dredge, so impacts would mostly be due to equilibration of the construction template to a natural shape by wave action rather than turbidity issues caused by dredging.

Nearshore hardbottom is in some portions of south Miami Beach. The nearshore of this area is the proposed borrow area for the beach fill in north Miami Beach. Out of the approximately 11,000 feet of shoreline length, approximately 3,700 feet of shoreline with hardbottom is within 600 feet of the beach. It may not be possible for dredges to operate in this area without causing impacts to hardbottom (otherwise requiring mitigation). Sufficient material is expected to be available using a dredge; however, if this is not the case, it is possible to excavate material in this area from the beach using a long-armed excavator, but this may increase project costs. Dredging material from the nearshore of south Miami Beach could ultimately conserve or increase hardbottom habitat in the area since the continuing accretion in the area is slowly covering more environmental resources.

A cutter suction dredge would most likely be used to by-pass and back-pass sand from the BHI Complex and South Beach sand sources. The back-passing of sand from the submerged nearshore areas of South Miami Beach could require the use of a booster pump to accommodate the distance that sand would need to be transported and the pipeline would run to the placement location either along the dry beach or in the water. For the BHI Complex by-passing previously used borrow areas in the ebb shoal and flood shoal will be used. Pipeline for the cutter suction dredging from South Beach would run either along the dry beach or nearshore areas, either submerged or floating, landward of any hardbottom resources to avoid any potential impacts. USACE anticipates using the existing pipeline corridors to transport sand dredged from the back-passing and by-passing areas to the beach placement sites. Establishing additional pipeline corridors could be beneficial to the construction schedule, cost, and productivity; therefore, the potential need and opportunity for additional corridors would be investigated further during the PED phase. If additional pipeline corridors are needed and identified, supplemental National Environmental Policy Act (NEPA) coordination would be conducted at that time. Mechanical equipment may also be used to dredge smaller quantities of sand to be back-passed from the dry beach portion of the South Beach sand source. Mechanical dredging from the dry beach could entail, but is not limited to, excavating material and truck hauling it to the placement areas or using mechanical equipment to load up a hopper that would pump material to the placement areas. Dredging will generally occur at least 400 feet away from hardbottom except for a portion of the borrow area located between R-67 to R-72. This portion of the South Beach sand source located within 400 feet of hardbottom would be completed in less than 18 days in compliance with the South Atlantic Regional Biological Opinion (SARBO) coral hardbottom project design criteria (PDCs). All the material to be by-passed or back-passed will have less than 5% fine material.

A hopper dredge would be used for the new offshore sand sources due to the water depths that they are located in. USACE anticipates using the existing pipeline corridors to transport sand dredged from offshore borrow sites to the beach placement area. Establishing additional pipeline corridors could be beneficial to the construction schedule, cost, and productivity; therefore, the potential need and opportunity for additional corridors would be investigated further during the PED phase. If additional pipeline corridors are needed and identified, supplemental NEPA would be conducted at that time. A 400-foot hardbottom buffer will be applied to all the new offshore borrow areas. Portions of these sand sources located within 400 to 1,000 feet of hardbottom would be completed in less than 18 days in compliance with the SARBO coral hardbottom PDCs. All the material to be used from the new offshore sand sources will have less than 5% fine material.

7.8 PROJECT MONITORING

Physical monitoring of the project is necessary to assess project performance and to ensure that project functionality is maintained throughout the 50-year project life. The monitoring plan will be directed primarily toward accomplishing systematic measurements of the beach profile shape. Profile surveys should provide accurate assessments of dune and beach fill volumes and provide a basis for assessing post-construction dune and beach fill adjustments, as well as variations in the profile shape due to seasonal changes and storms. Monitoring will play a vital role in determining if project renourishment is necessary. Post-construction monitoring activities include topographic and bathymetric surveys of the placement area on an annual basis following construction. The cost for this post-construction monitoring is included in the cost-shared total project cost.

Other monitoring efforts include bathymetric mapping of the borrow sites, which will be done as part of the pre-construction engineering and design (PED) phase prior to each nourishment.

Measured wind, wave, and water-level information will be obtained from the best available existing data sources. This data will be applied in support of previously discussed monitoring efforts. It will also be used to periodically assess the state of sea-level rise and to determine if a reassessment of the project volumes and/or renourishment intervals is needed.

8 PROJECT SUMMARY

This appendix summarizes the engineering design of a shore-protection project proposed for construction in Miami-Dade County, Florida (Main Segment and Key Biscayne Segment). The project consists of beach nourishment and renourishment along portions of the Main Segment and Key Biscayne as follows:

- Village of Bal Harbour/Town of Surfside - Model Reaches R027 to R034 (R-27 to R-34.5)
- North Miami Beach - Model Reaches R040 to R056 (R-39.5 to R-56.5)
- Key Biscayne - Model Reaches R102 to R107 (R-101.3 to R-108)

The design beach fill template for the Village of Bal Harbour/Town of Surfside is characterized by enhancement/construction of a uniform dune to a 9.5-foot NAVD88 elevation, a 20-foot-wide dune crest, and a 25-foot berm width at 7 feet NAVD88. The design beach fill template for North Miami Beach includes a uniform dune with a 9.5-foot NAVD88 elevation, a 20-foot-wide dune crest, and a 25-foot berm width at 7 feet NAVD88. The design beach fill template for Key Biscayne includes a uniform dune crest at 11 feet NAVD88, a 15-foot-wide dune crest, and a 5-foot berm width at 4 feet NAVD88 (R-101.3 to R-103) or 3 feet-NAVD88 (R-103 to R-108). Beach material required under the High SLC scenario includes an average of 633,500 cy for initial construction of the Main Segment and 854,100 cy every four years until the end of Federal participation. For the Key Biscayne Segment, beach material required under the High SLC scenario includes an average of 26,200 cy for initial construction and 24,500 cy every two years until the end of Federal participation. It should be noted that in practice, renourishment requirements are influenced by storm events and long-term erosion and may experience some variability due to the uncertainty inherent in natural phenomenon.

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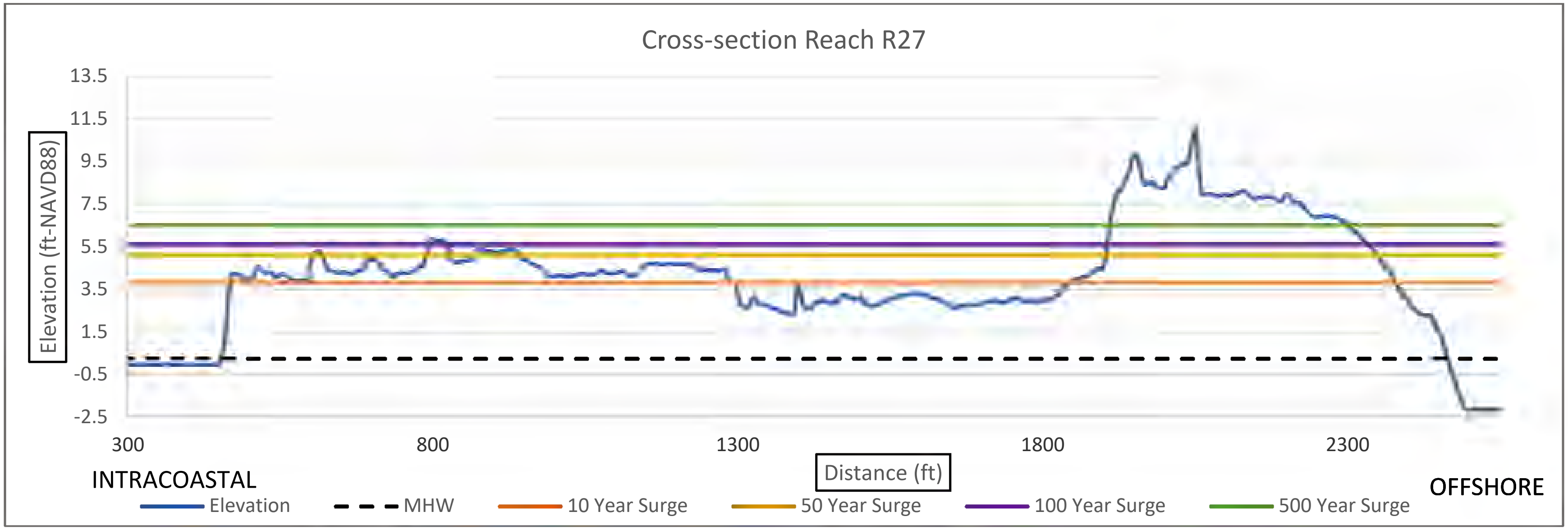
Attachment 1

Miami-Dade County Main Segment and Key Biscayne Cross-Sections

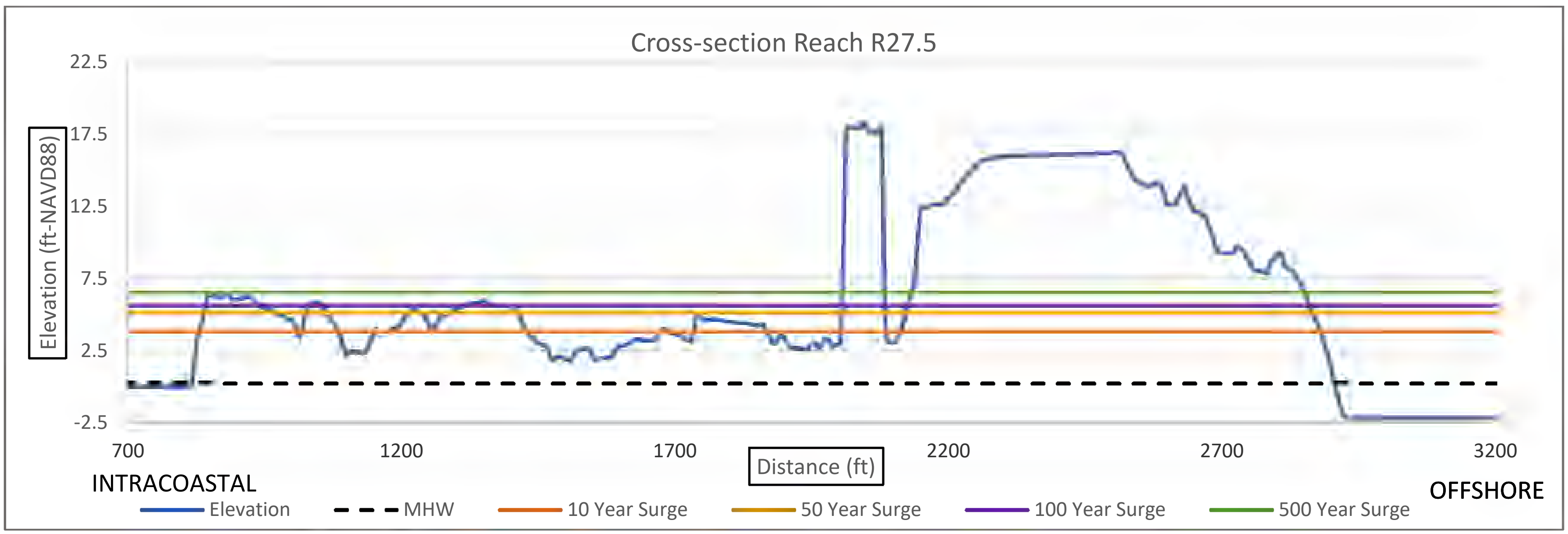
The following pages show the cross-sections across the Miami-Dade County Main Segment and Key Biscayne project areas. These cross-sections are taken at FDEP R-monuments and at intermediate monuments where available between R-27 and R-74 and R-101 and R-108. These cross-sections show the elevations across the extents of the barrier islands that comprise the project area. Also included on the cross-sections are storm surge elevations between the 10-year and 500-year return periods. The storm surge elevations were taken from the FEMA Flood Insurance Study (FIS) at R-56 (Table 1) for the Main Segment. Actual storm surge values along the shoreline are shown to vary, but these values give a representative approximation for the expected storm surges in the project area. Water levels on the back side of the barrier islands for similar return periods may also vary. The values used for Key Biscayne (Table 1) were also obtained from the FEMA FIS for R-106.

Table 1: Storm Surge Elevations

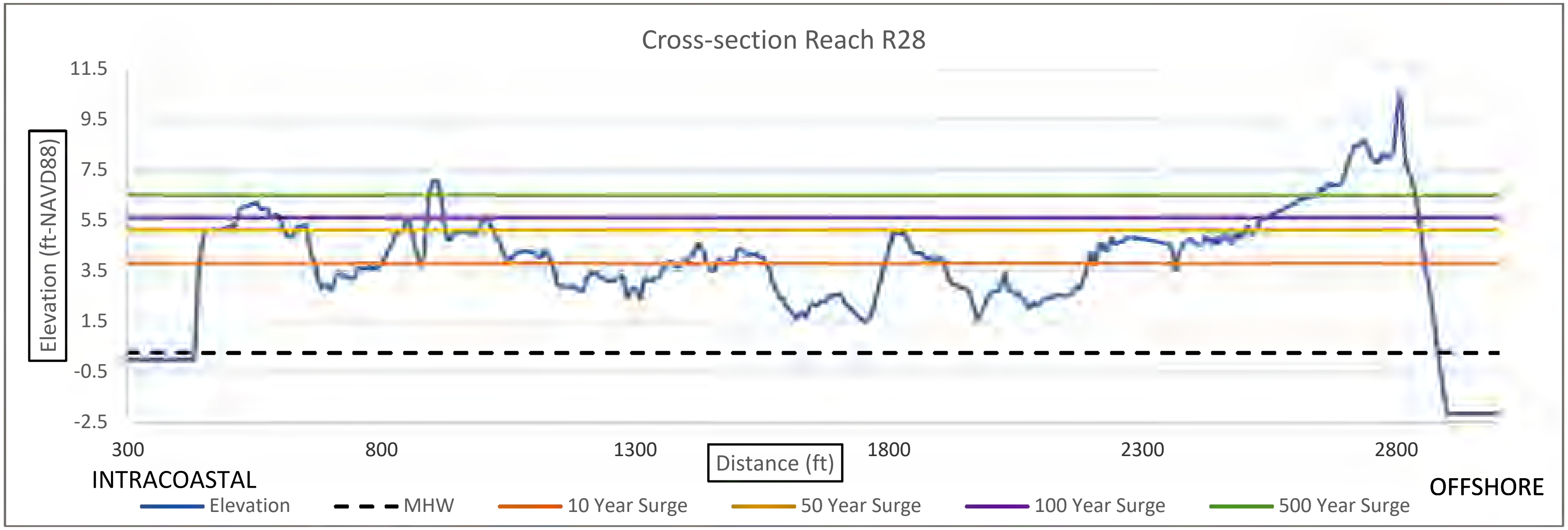
Return Period (Yrs)	Storm Surge R-56 (ft NAVD88)	Storm Surge R-106 (ft NAVD88)
10	3.8	4.0
50	5.1	5.3
100	5.6	5.7
500	6.5	6.8

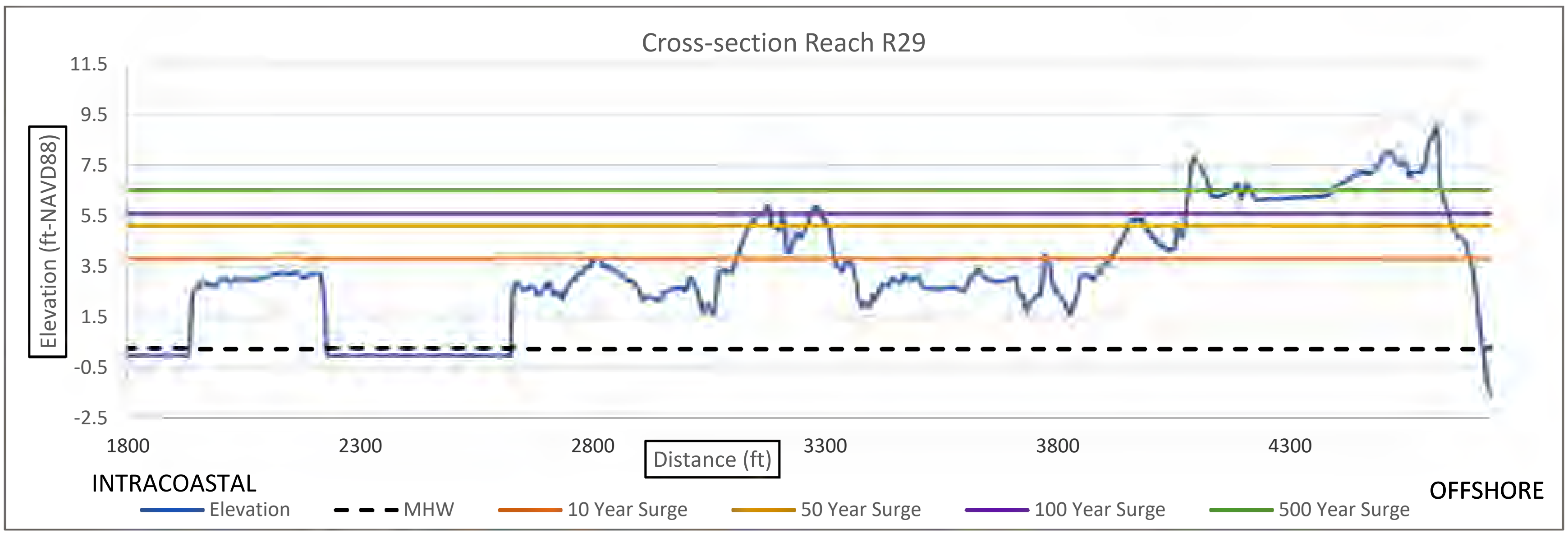


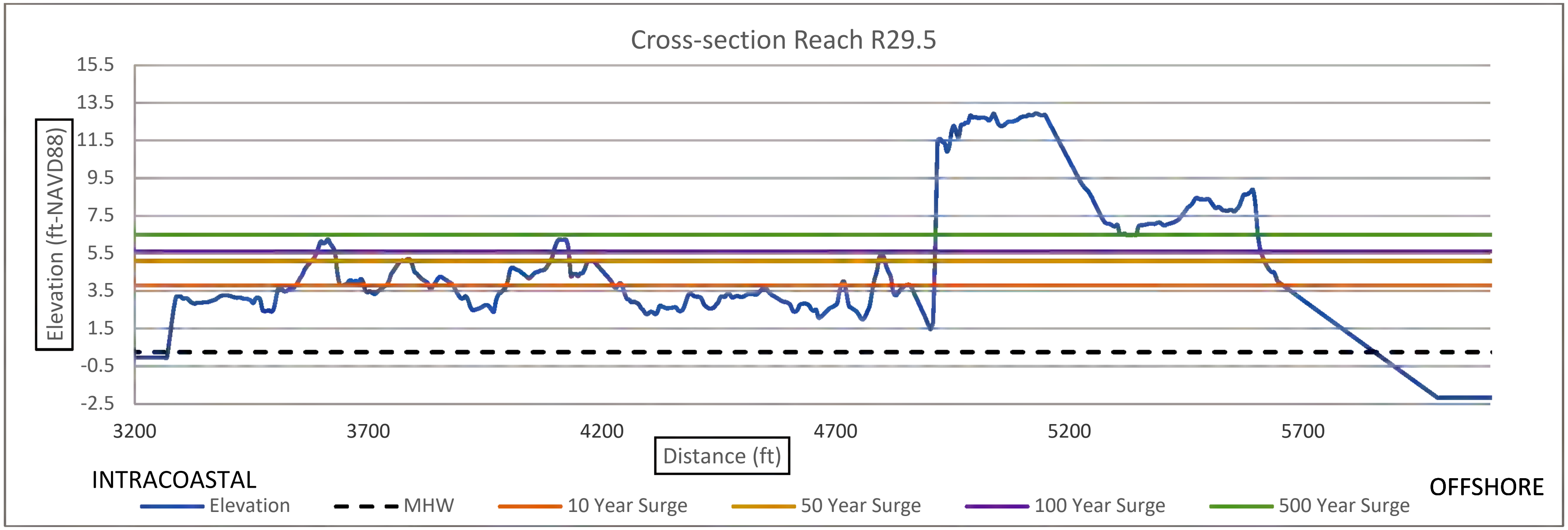
Cross-section Reach R27
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
300
800
1300
1800
2300
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

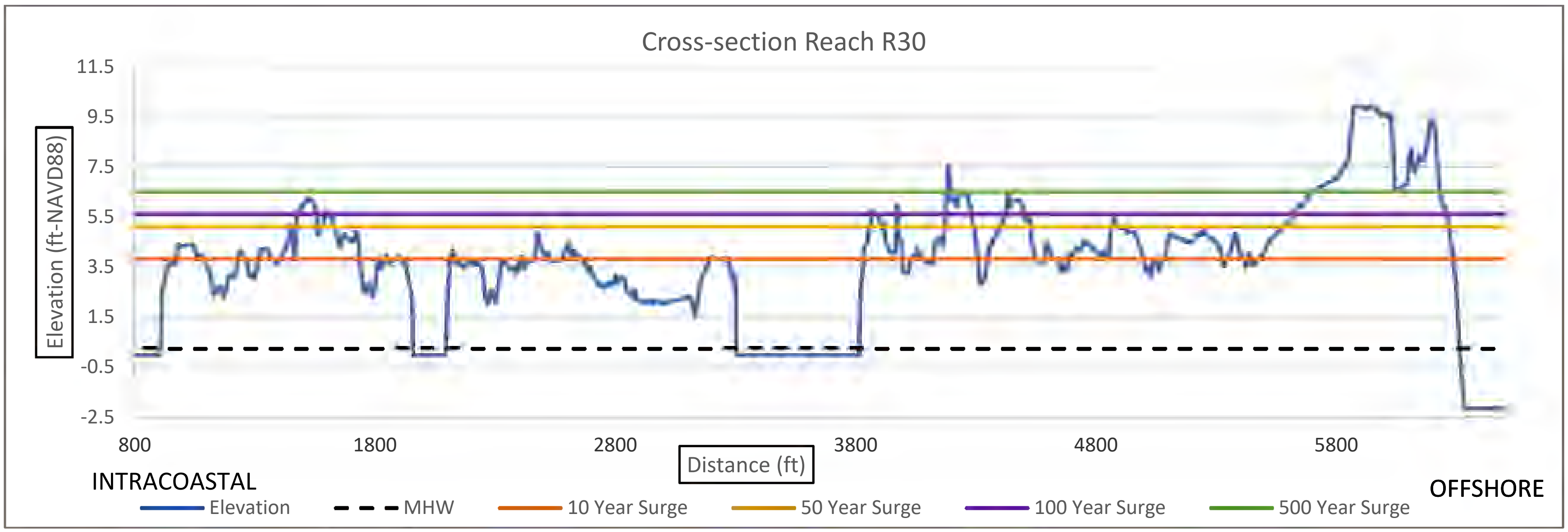


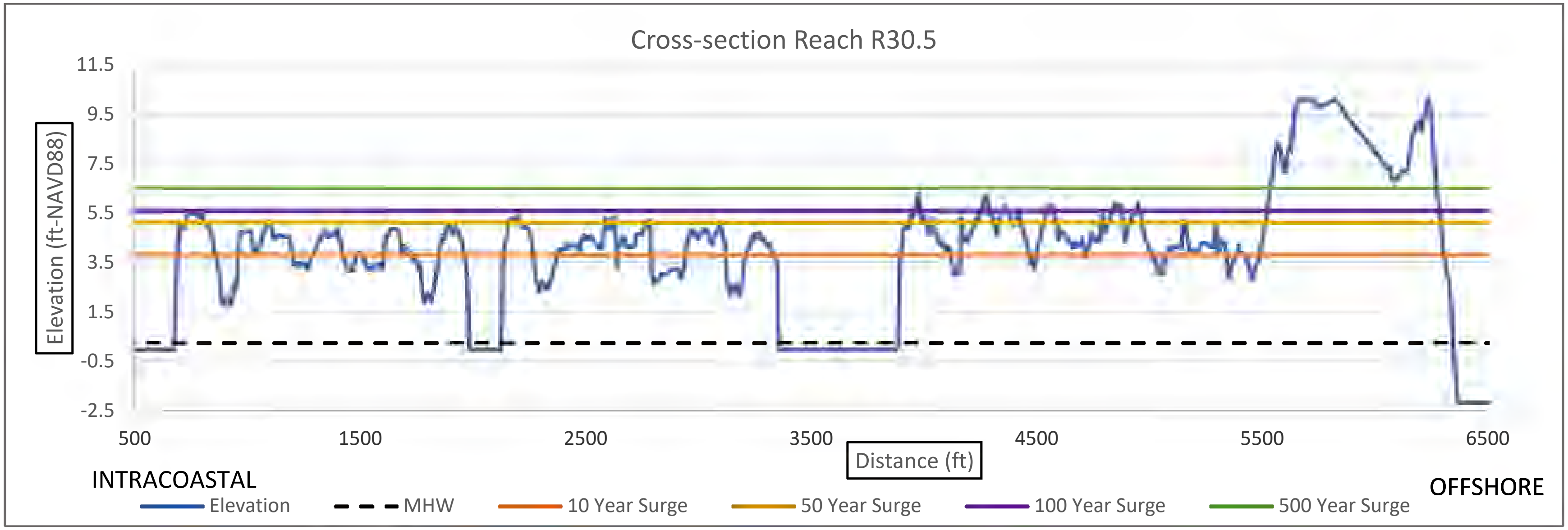
Cross-section Reach R27.5
22.5
17.5
12.5
7.5
2.5
-2.5
Elevation (ft-NAVD88)
700
1200
1700
2200
2700
3200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

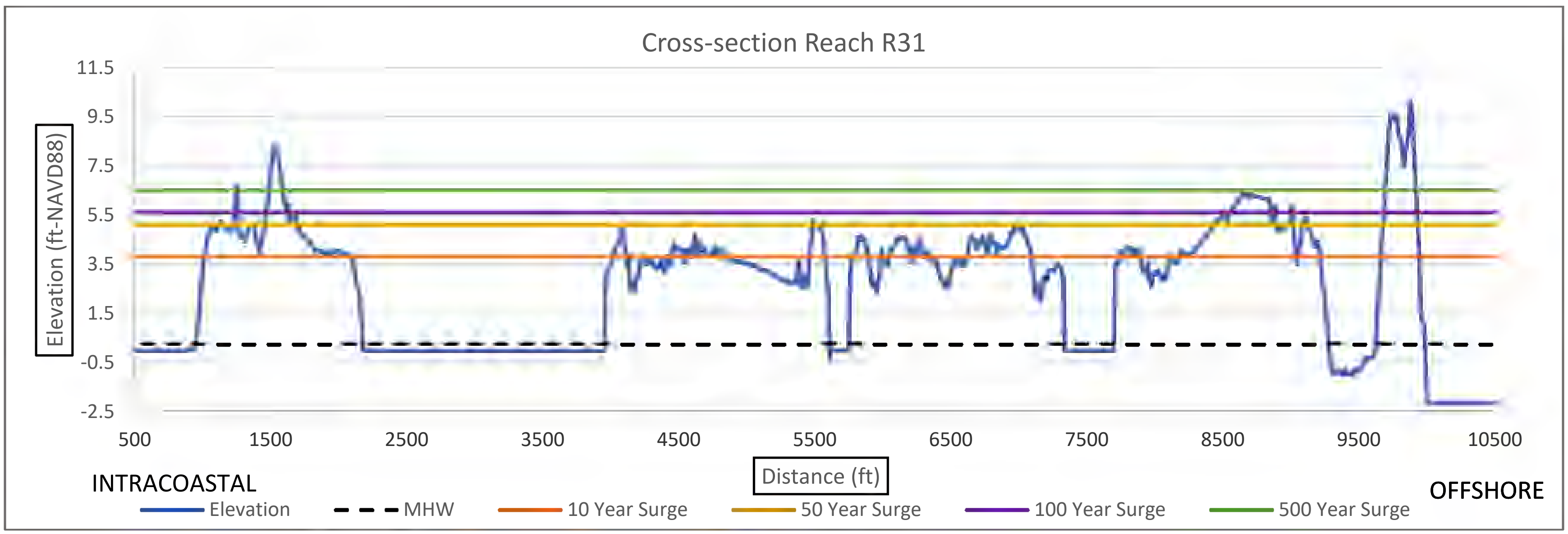

Cross-section Reach R28
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
300
800
1300
1800
2300
2800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

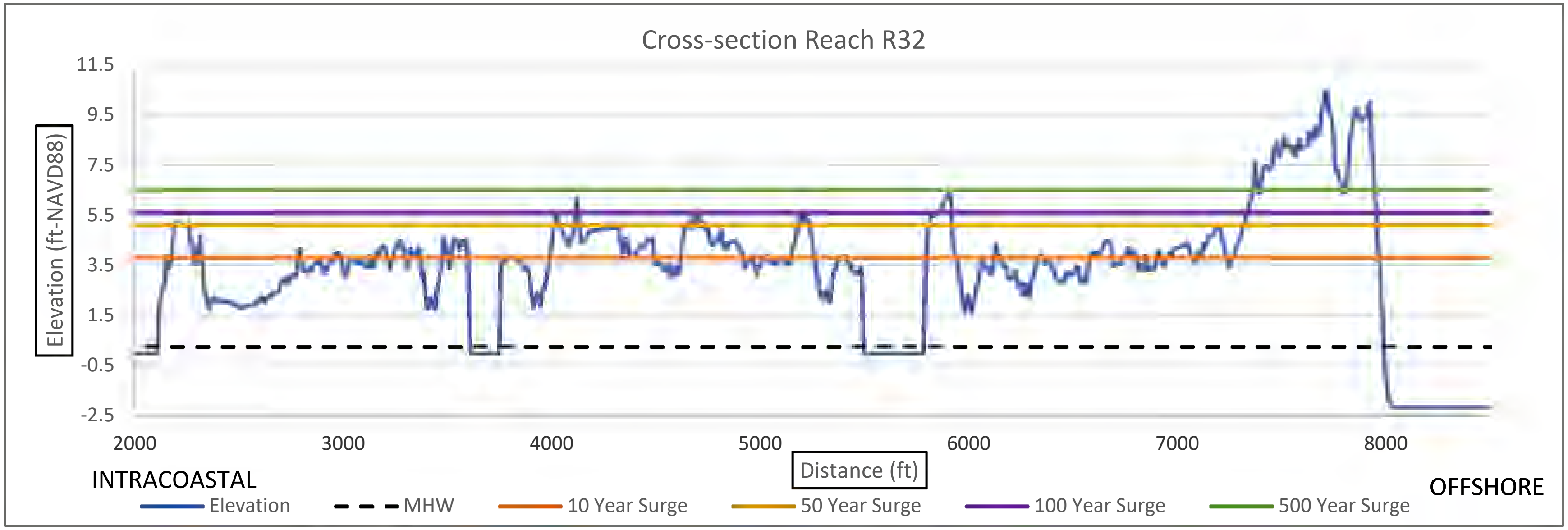

Cross-section Reach R29
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
1800
2300
2800
3300
3800
4300
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

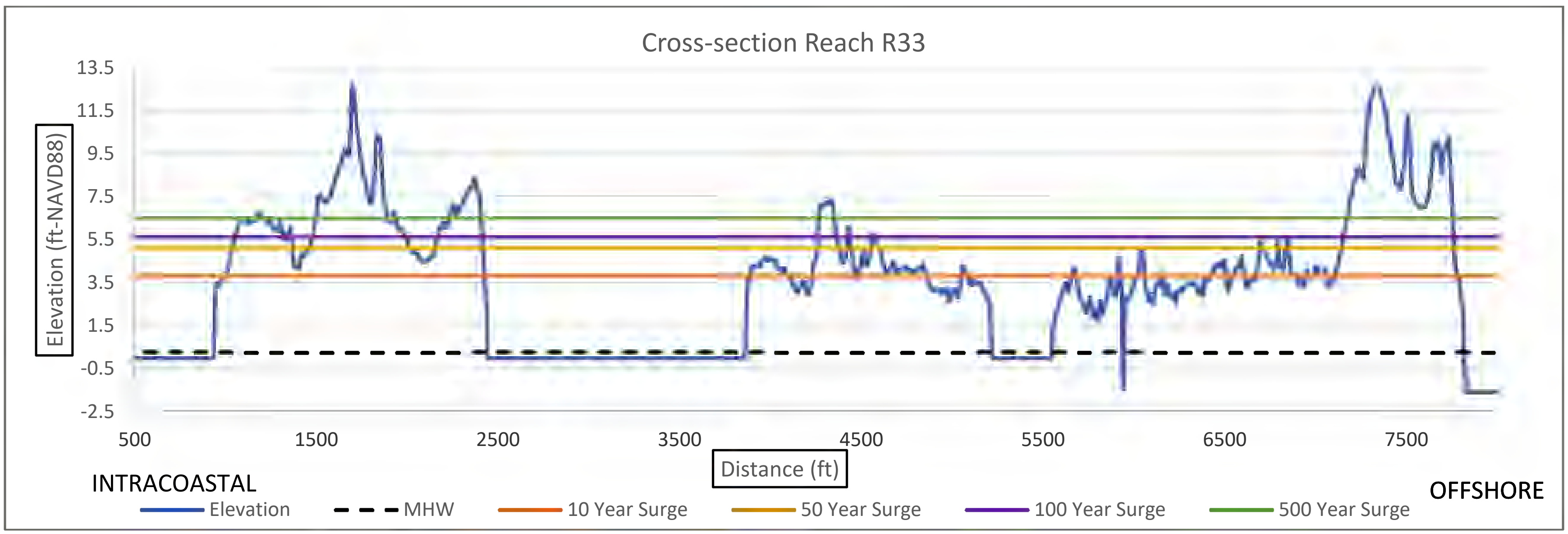

Cross-section Reach R29.5
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
3200
3700
4200
4700
5200
5700
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

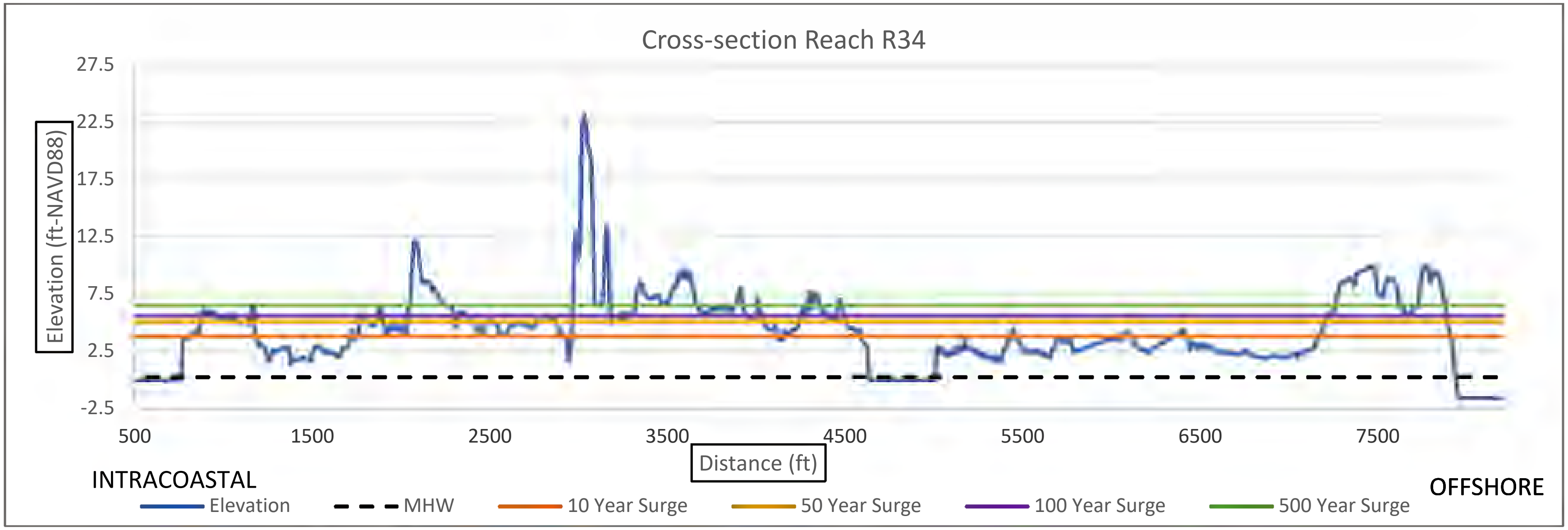

Cross-section Reach R30
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
800
1800
2800
3800
4800
5800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

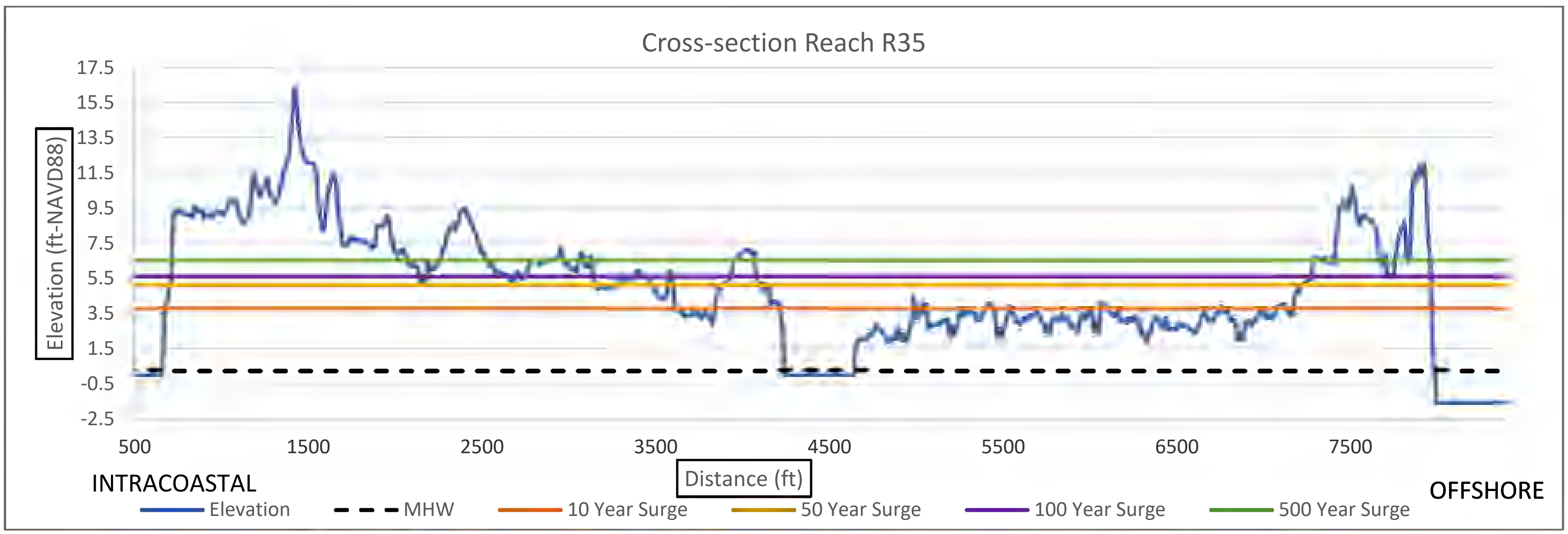

Cross-section Reach R30.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
500
1500
2500
3500
4500
5500
6500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

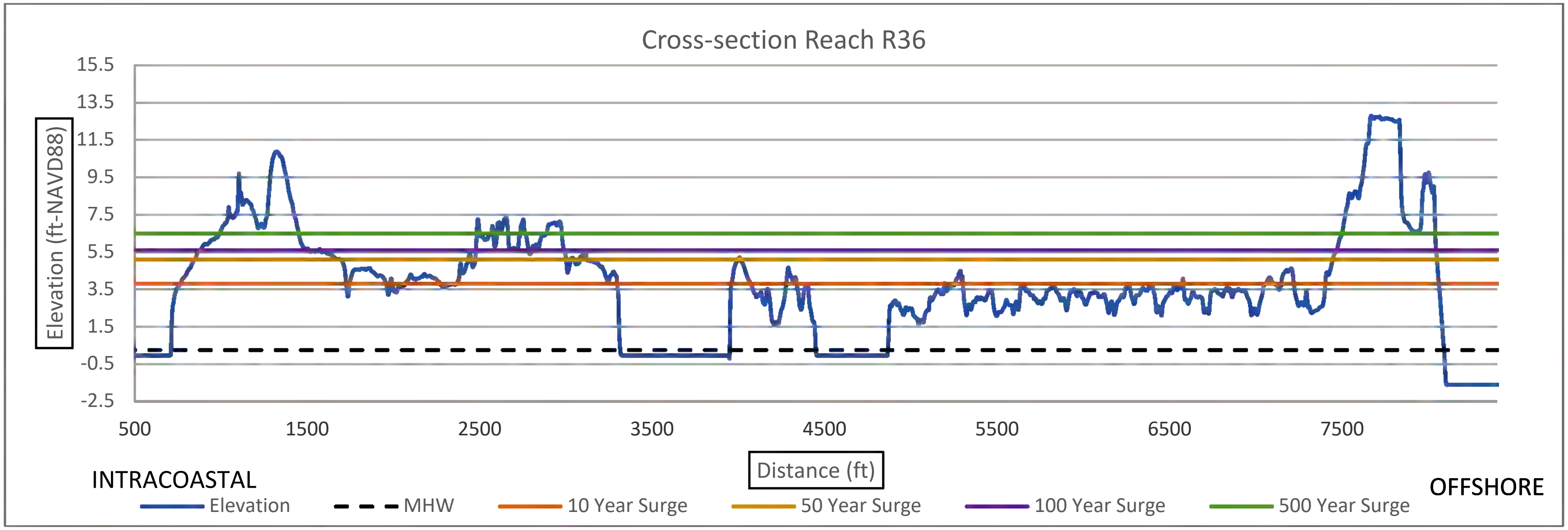

Cross-section Reach R31
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
500
1500
2500
3500
4500
5500
6500
7500
8500
9500
10500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

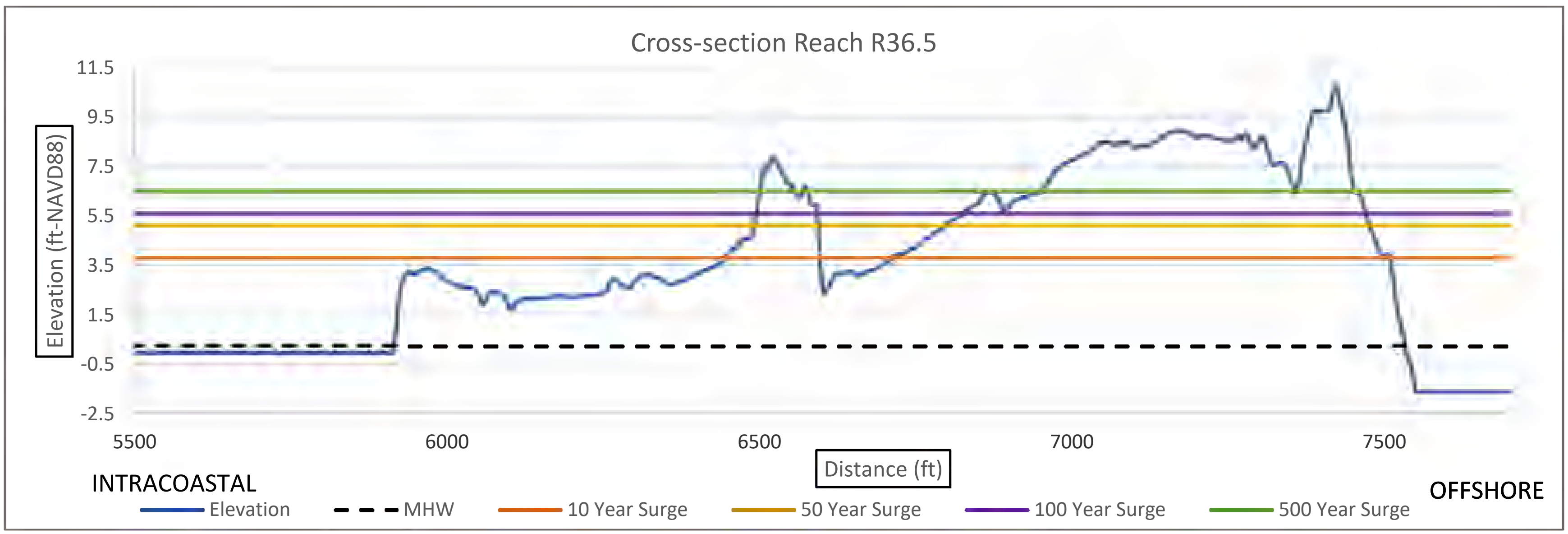

Cross-section Reach R32
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

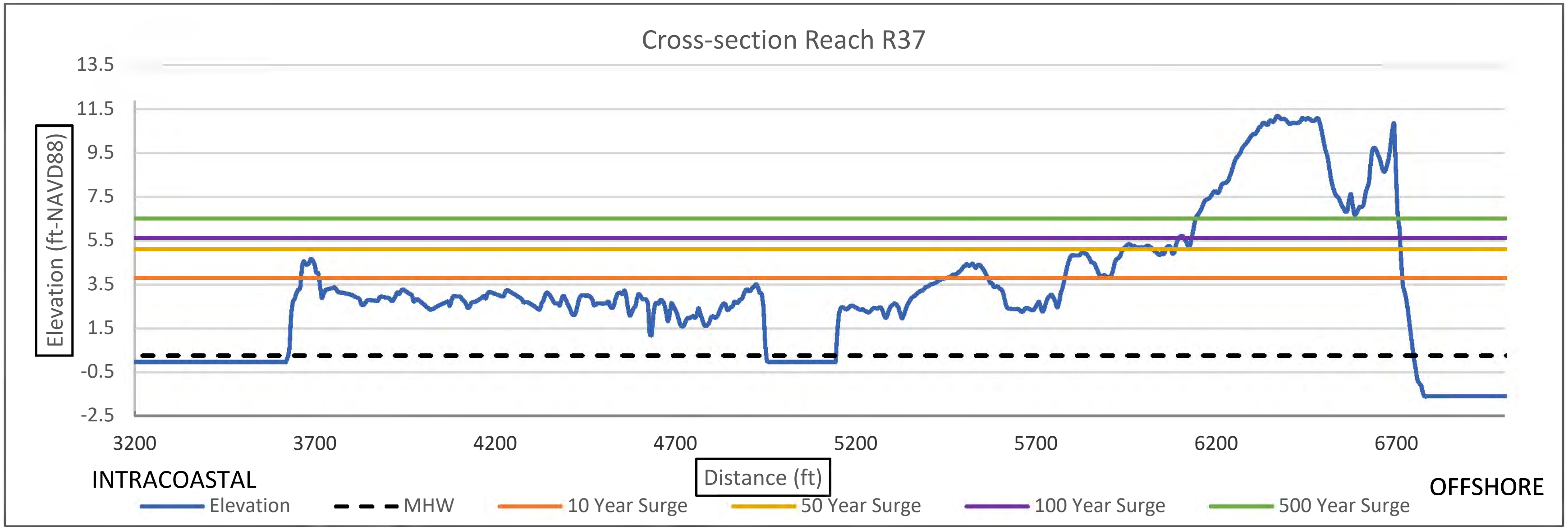

Cross-section Reach R33
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
500
1500
2500
3500
4500
5500
6500
7500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

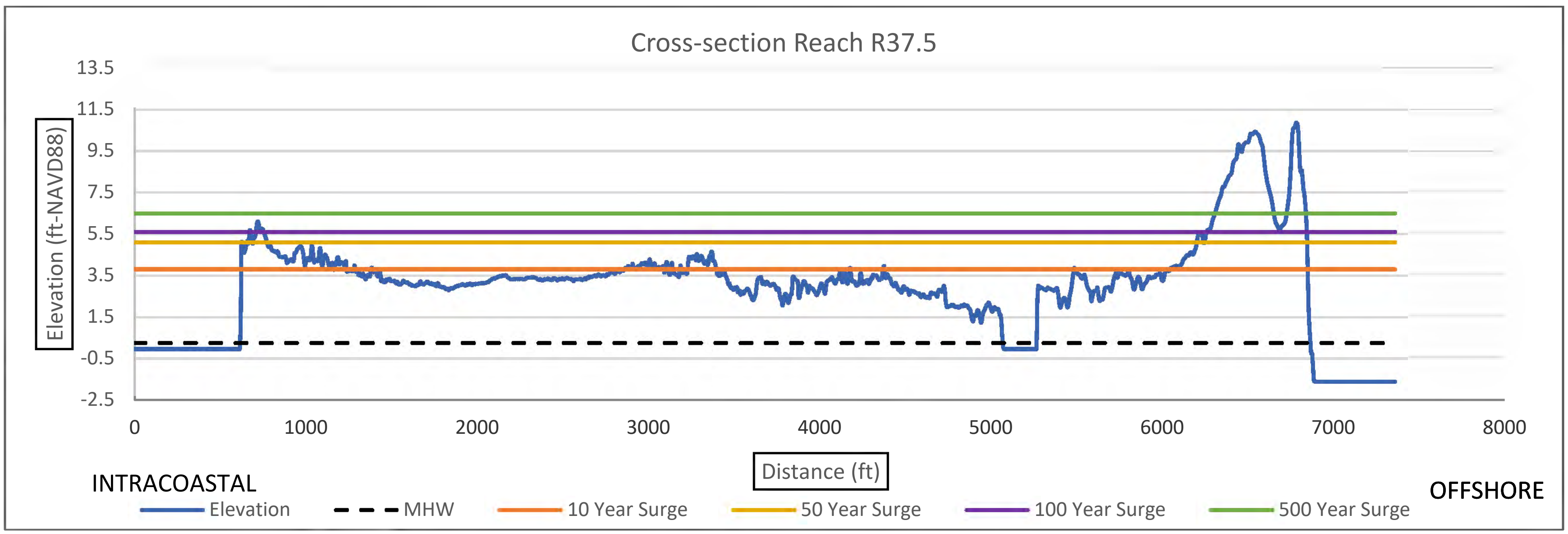

Cross-section Reach R34
Elevation (ft-NAVD88)
27.5
22.5
17.5
12.5
7.5
2.5
-2.5
500
1500
2500
3500
4500
5500
6500
7500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

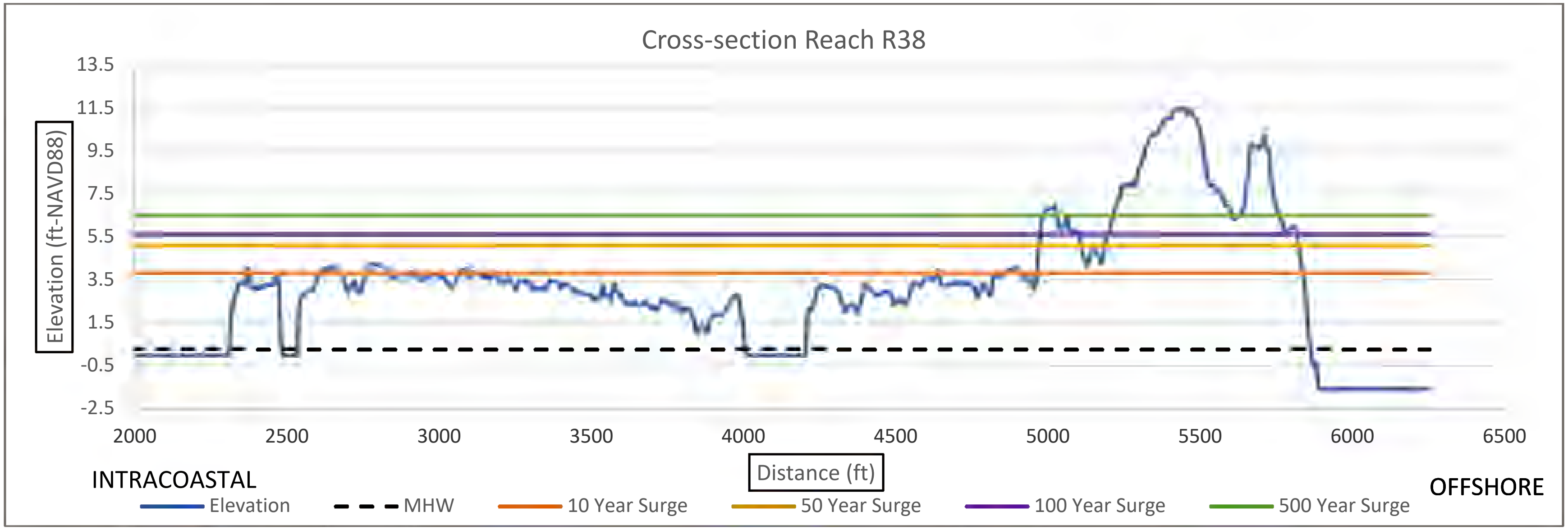

Cross-section Reach R35
Elevation (ft-NAVD88)
17.5
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
500
1500
2500
3500
4500
5500
6500
7500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

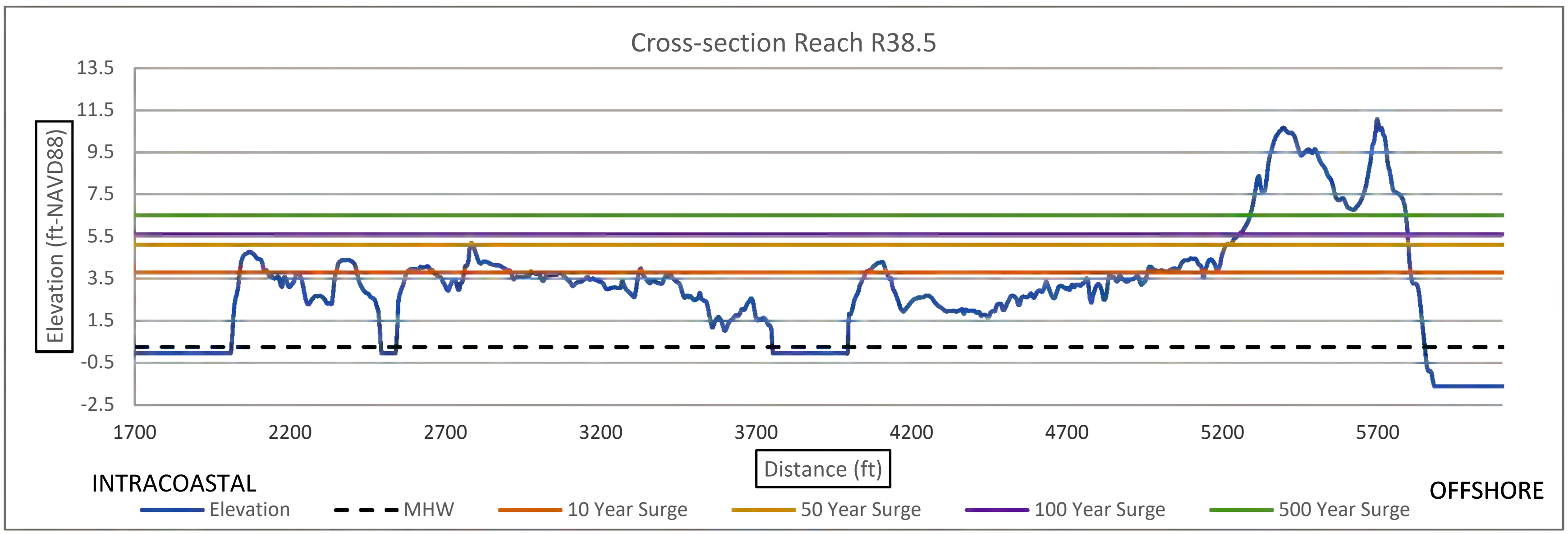

Cross-section Reach R36
Elevation (ft-NAVD88)
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
500
1500
2500
3500
4500
5500
6500
7500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

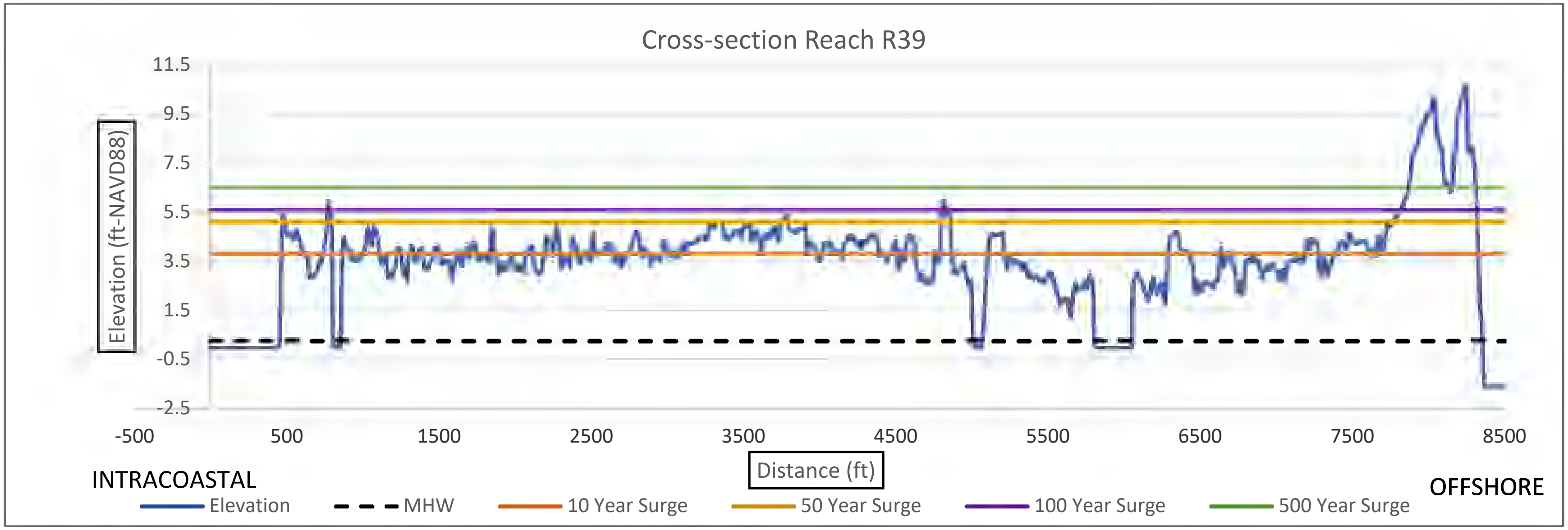

Cross-section Reach R36.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
5500
6000
6500
7000
7500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

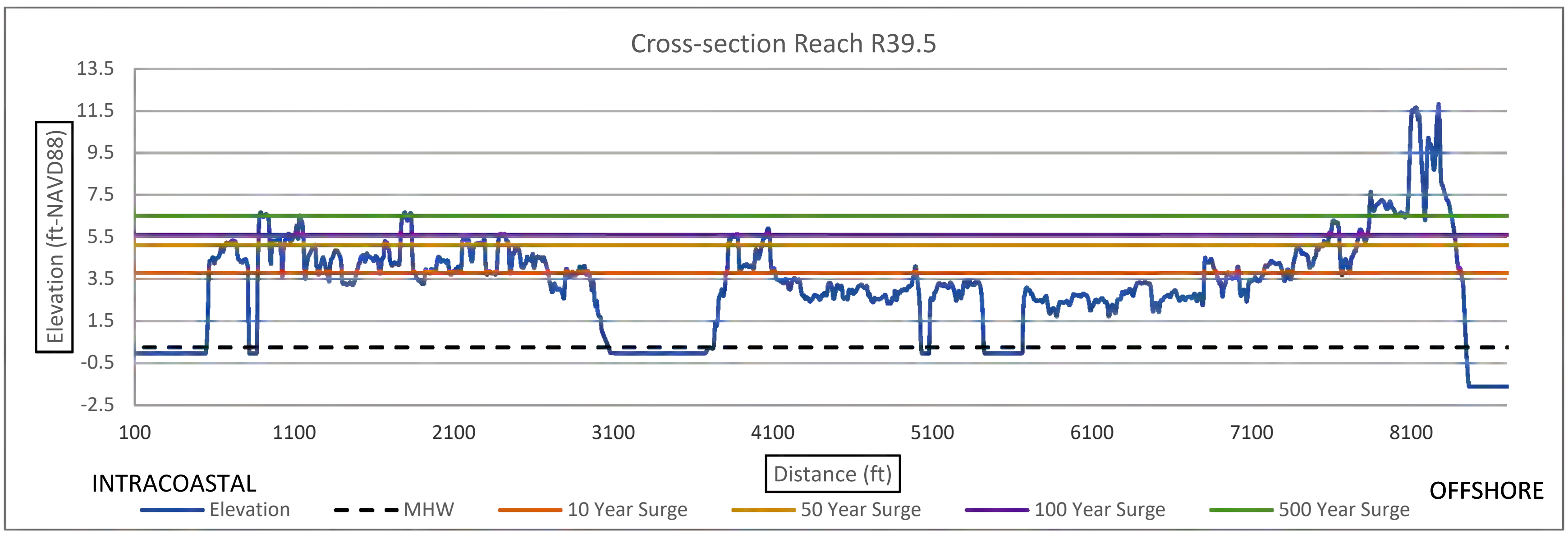

Cross-section Reach R37
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
3200
3700
4200
4700
5200
5700
6200
6700
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

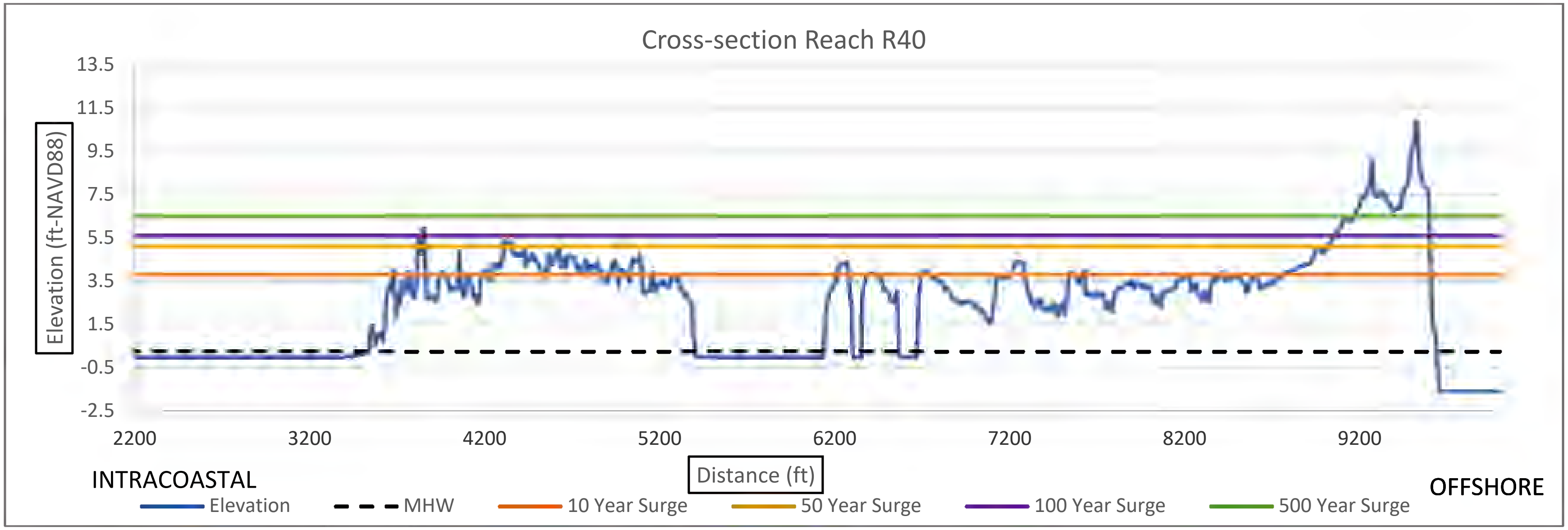

Cross-section Reach R37.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

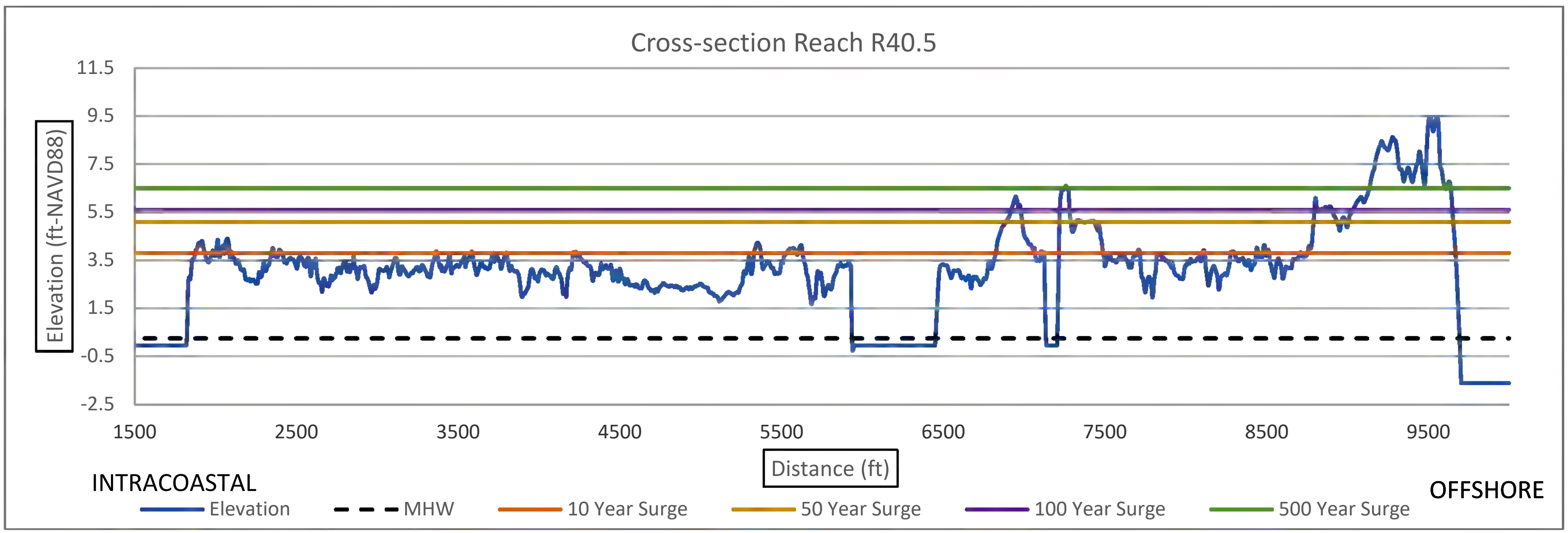

Cross-section Reach R38
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

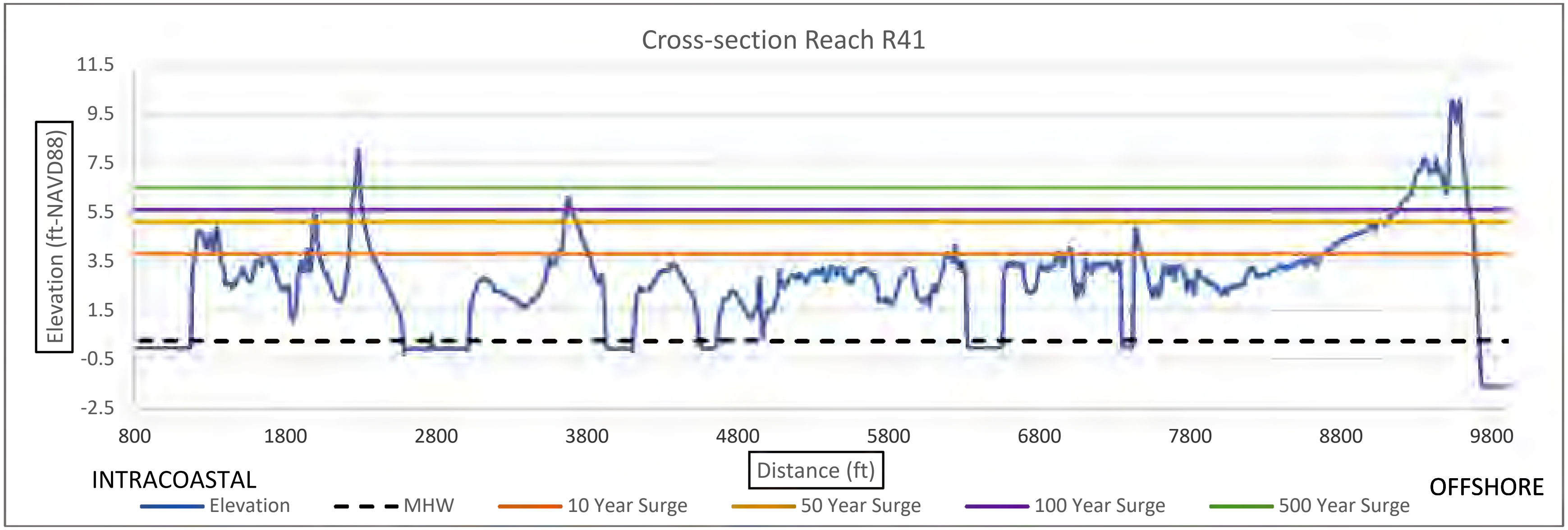

Cross-section Reach R38.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
1700
2200
2700
3200
3700
4200
4700
5200
5700
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

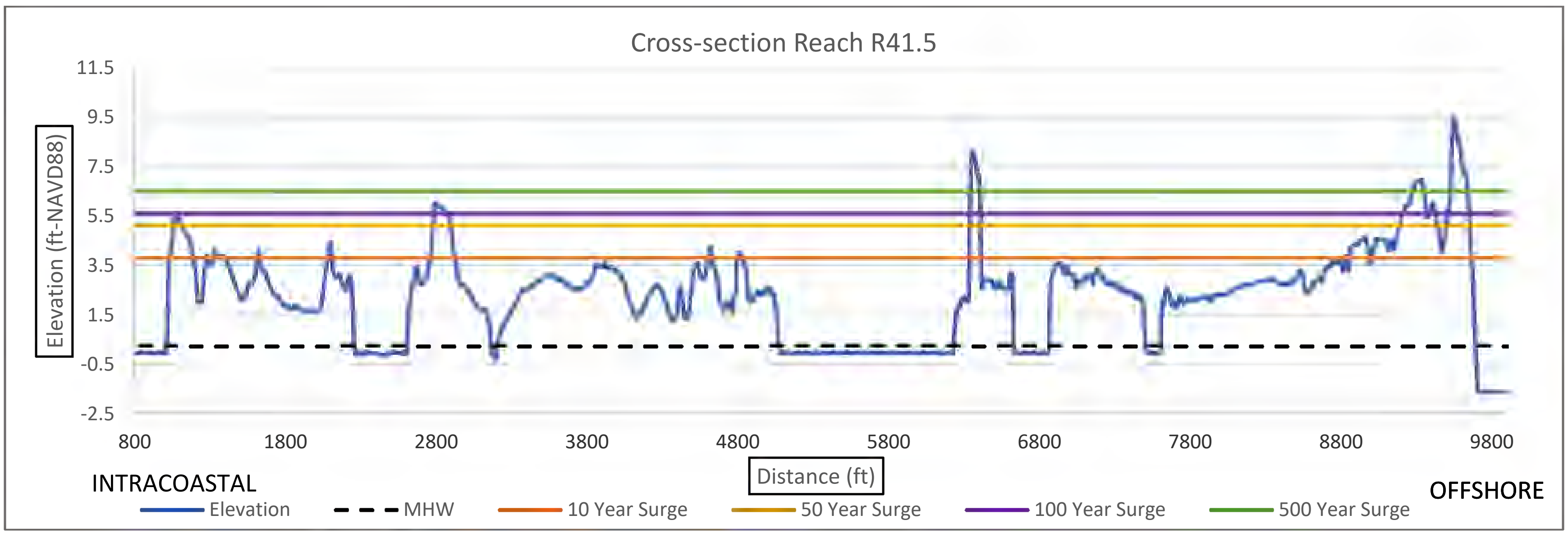

Cross-section Reach R39
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
-500
500
1500
2500
3500
4500
5500
6500
7500
8500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

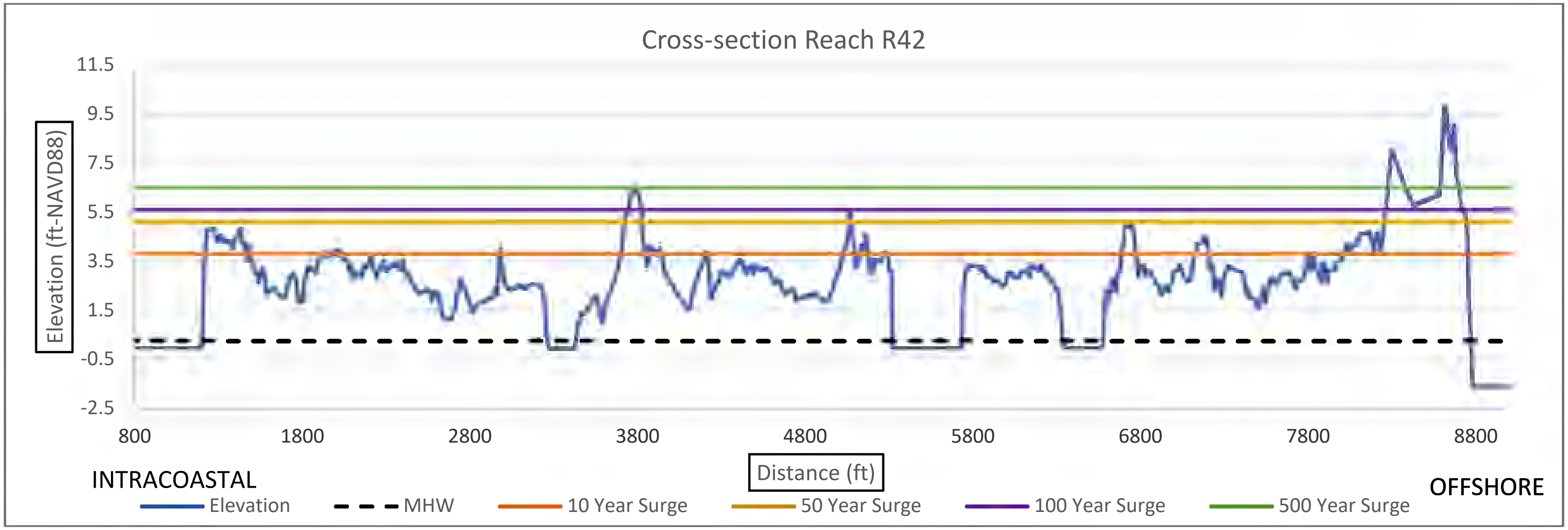

Cross-section Reach R39.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
100
1100
2100
3100
4100
5100
6100
7100
8100
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

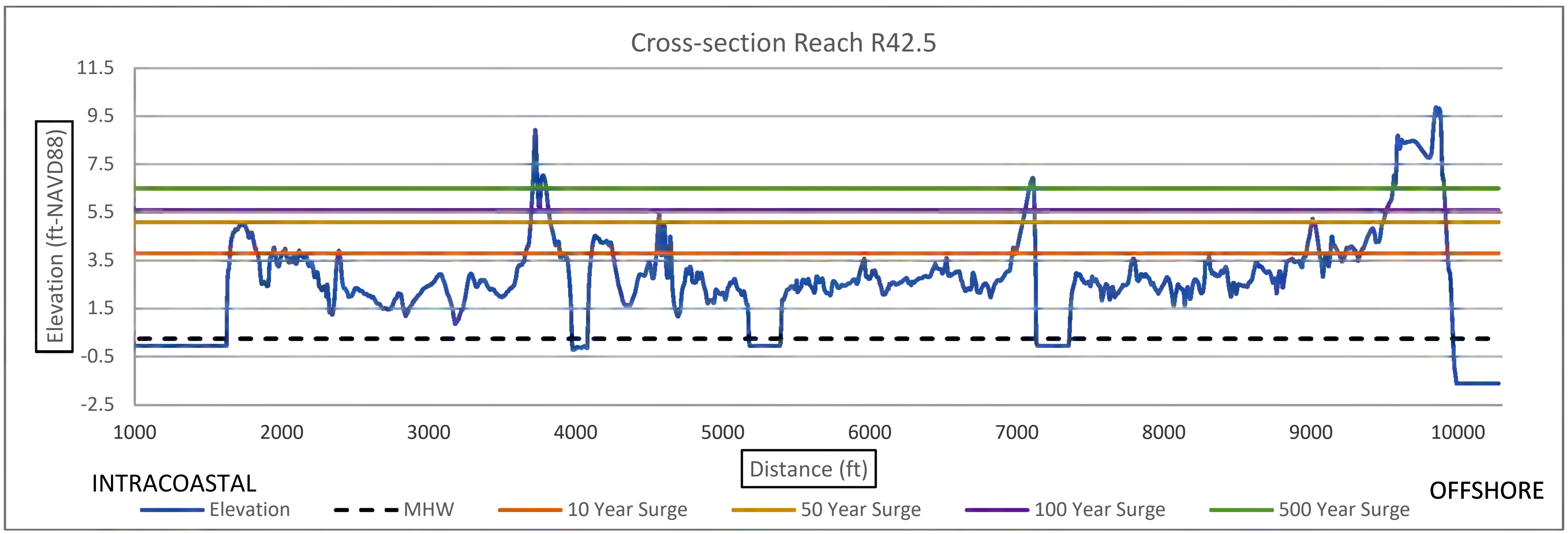

Cross-section Reach R40
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
2200
3200
4200
5200
6200
7200
8200
9200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

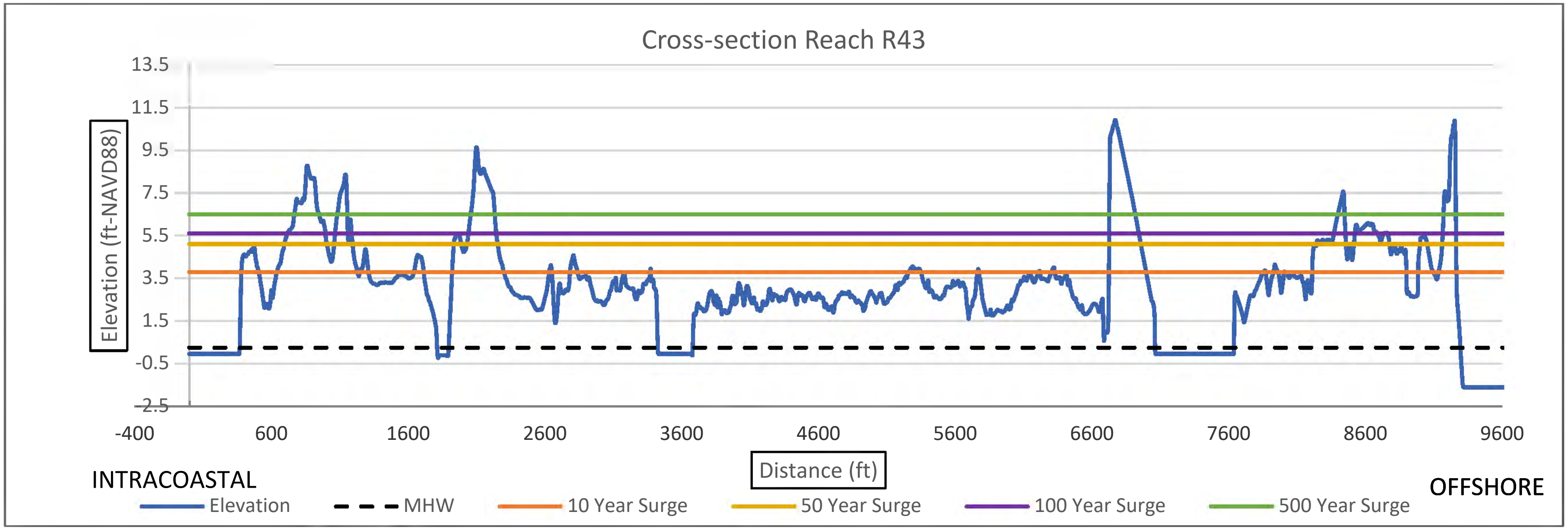

Cross-section Reach R40.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
1500
2500
3500
4500
5500
6500
7500
8500
9500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

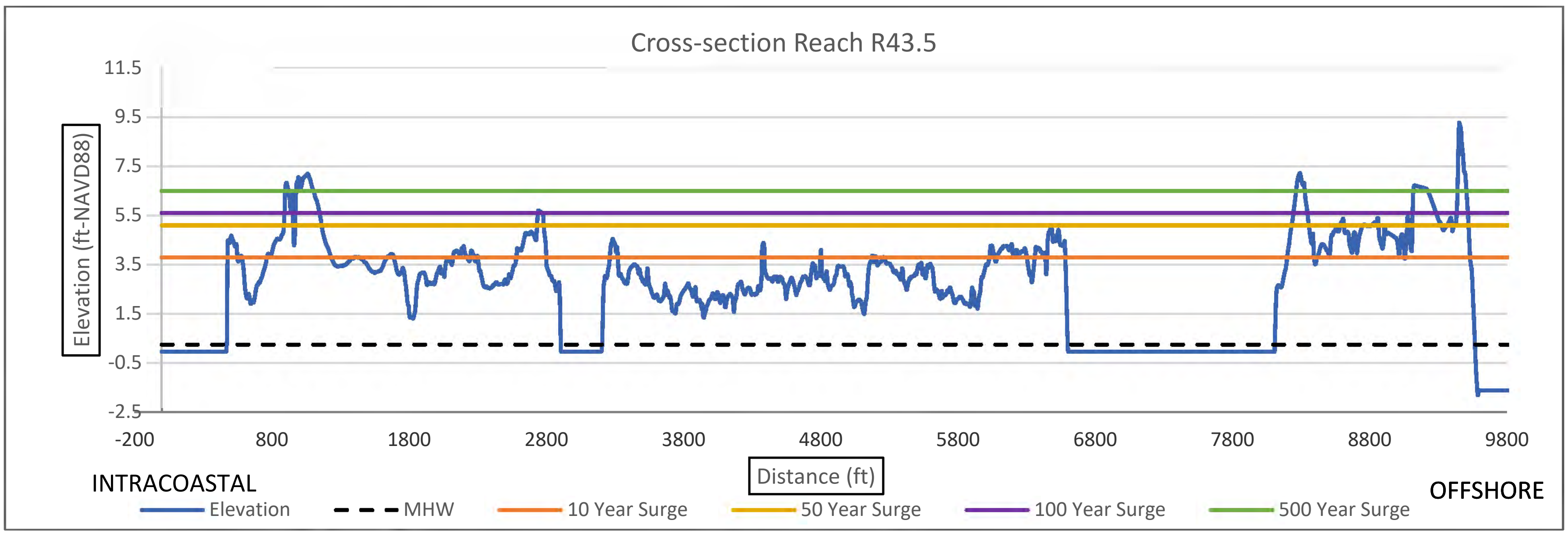

Cross-section Reach R41
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
800
1800
2800
3800
4800
5800
6800
7800
8800
9800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

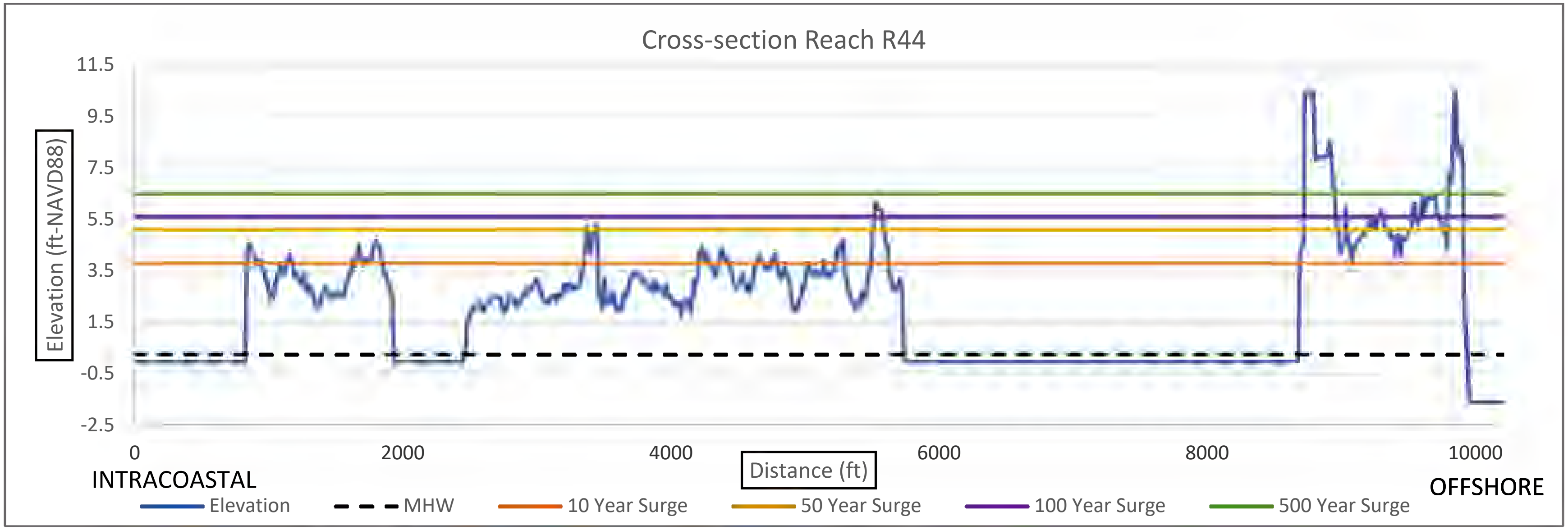

Cross-section Reach R41.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
800
1800
2800
3800
4800
5800
6800
7800
8800
9800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

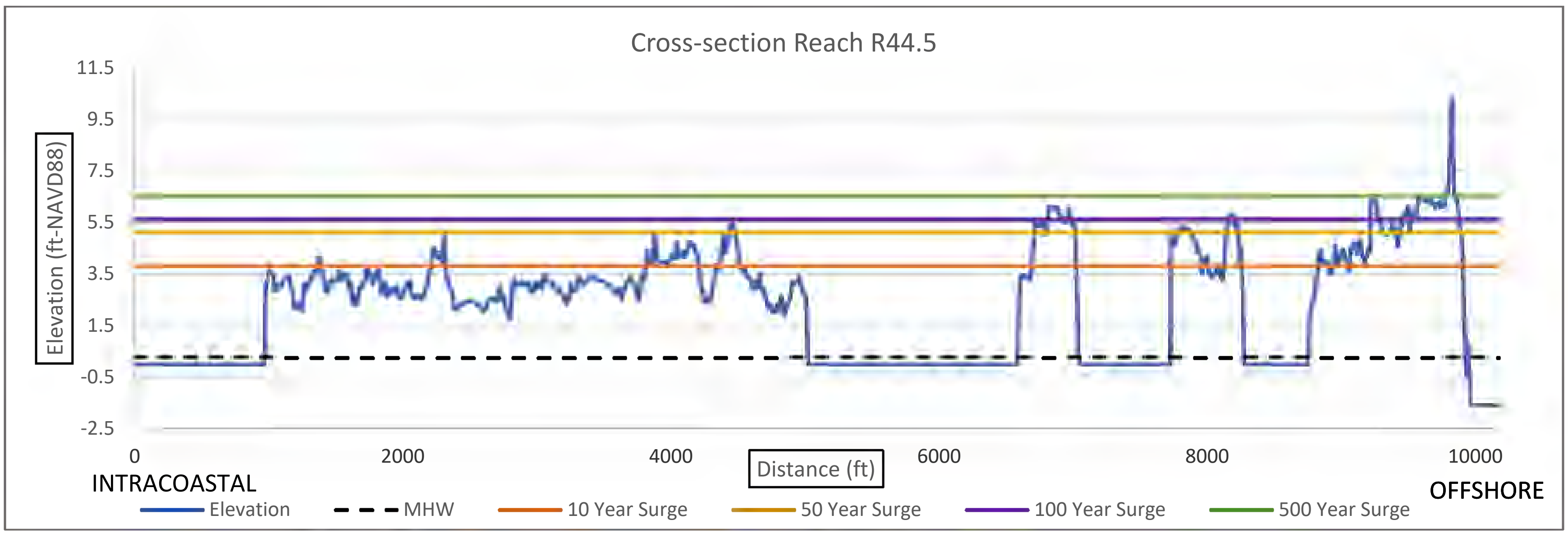

Cross-section Reach R42
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
800
1800
2800
3800
4800
5800
6800
7800
8800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

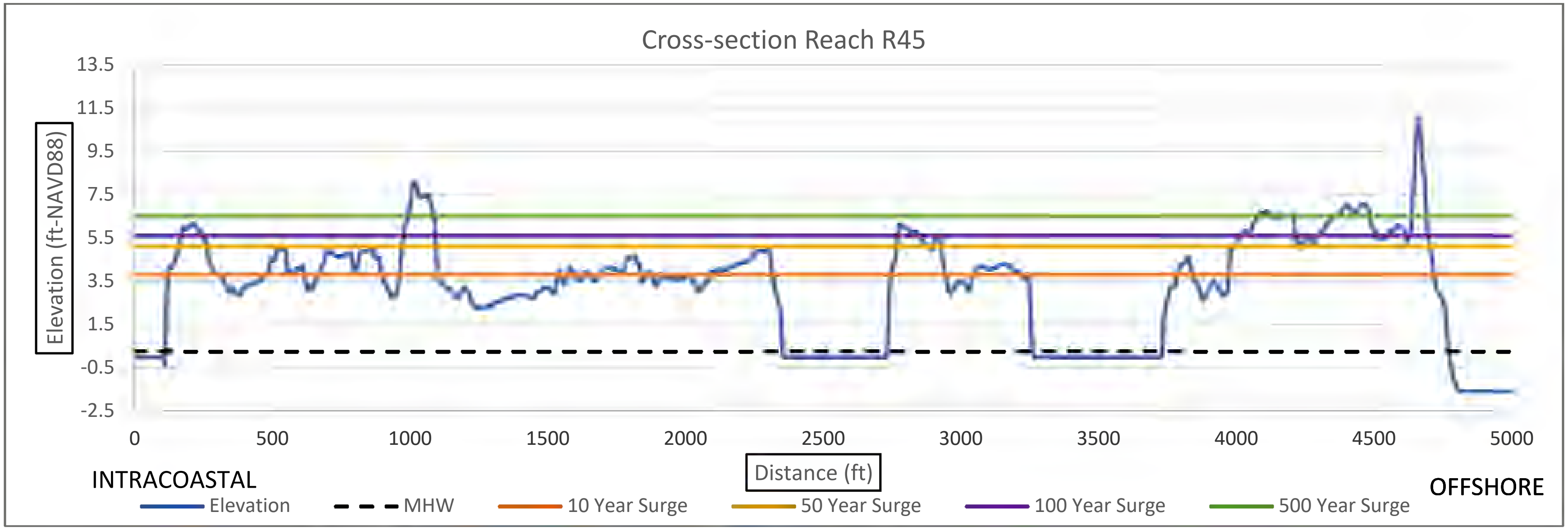

Cross-section Reach R42.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R43
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
-400
600
1600
2600
3600
4600
5600
6600
7600
8600
9600
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

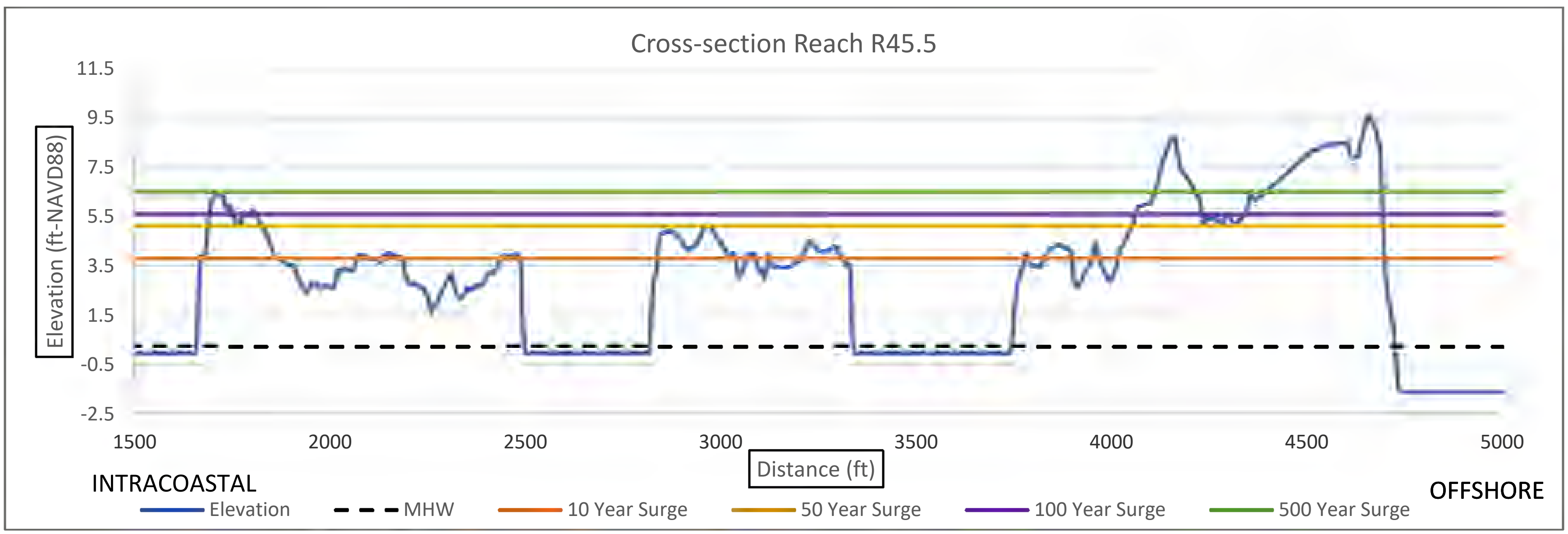

Cross-section Reach R43.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
-200
800
1800
2800
3800
4800
5800
6800
7800
8800
9800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R44
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
2000
4000
6000
8000
10000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

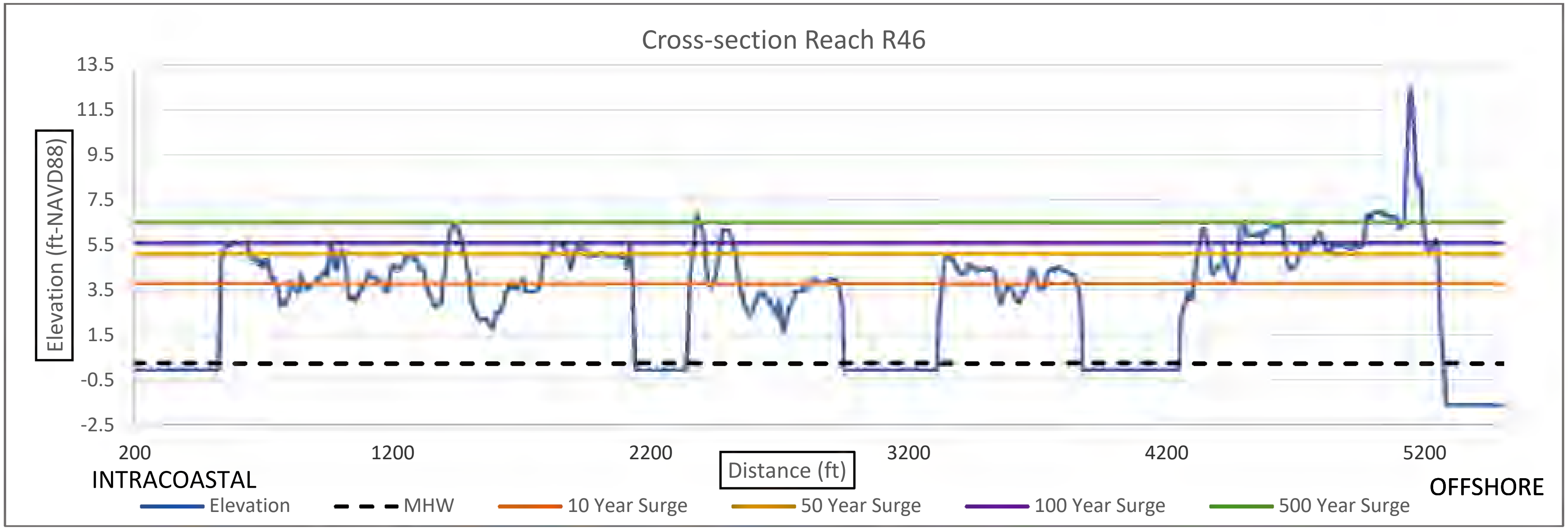

Cross-section Reach R44.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
2000
4000
6000
8000
10000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

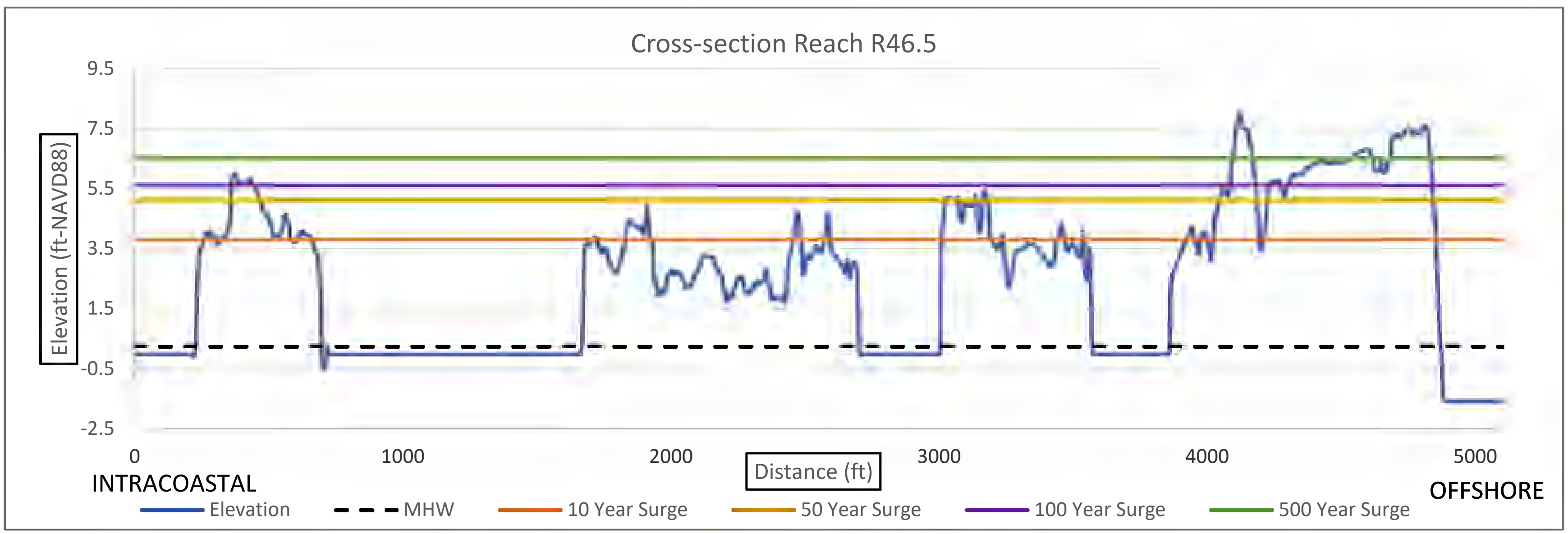


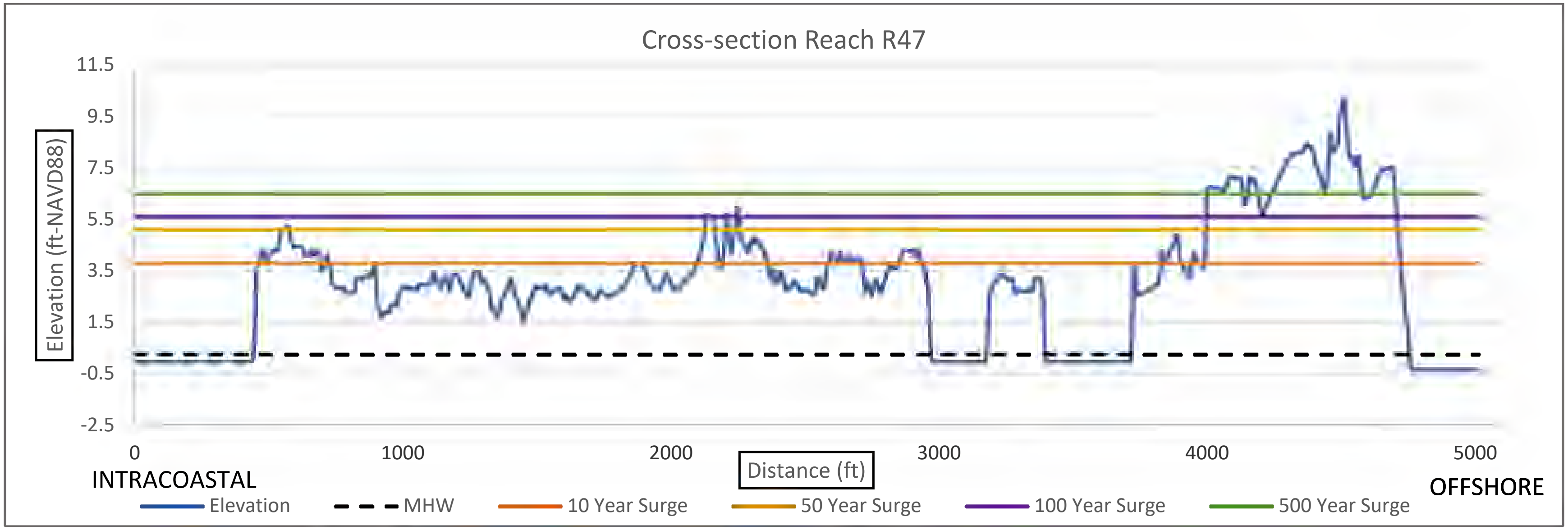
Cross-section Reach R45
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

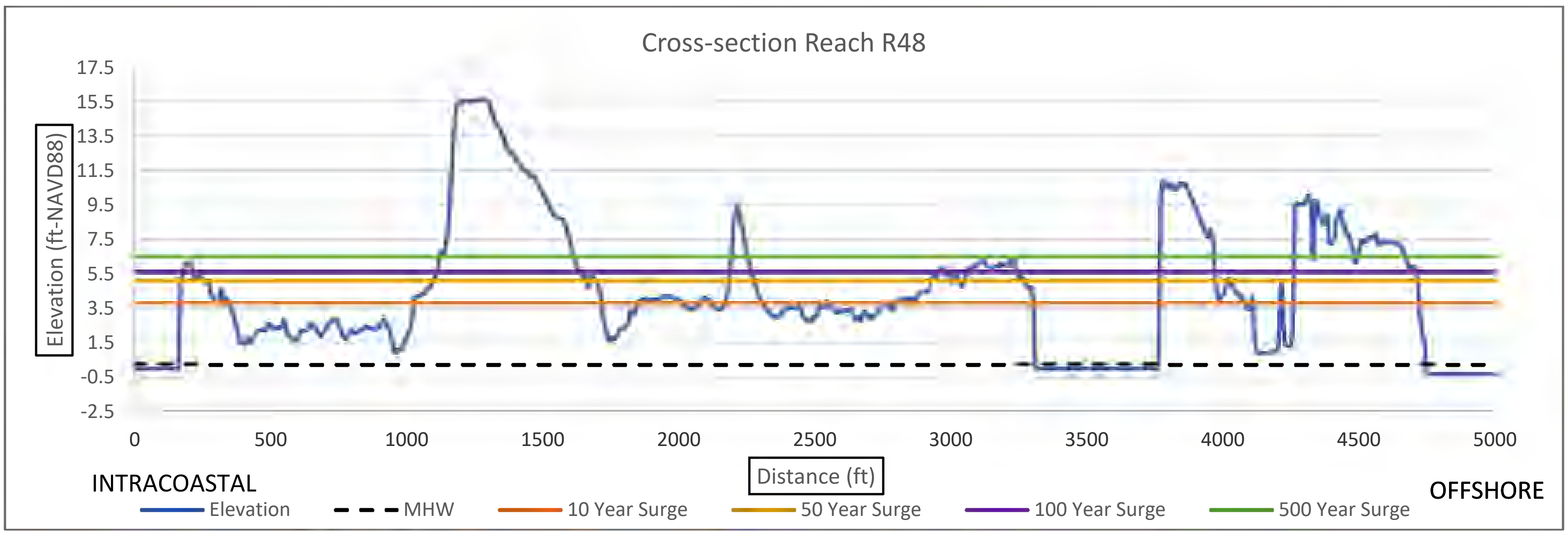


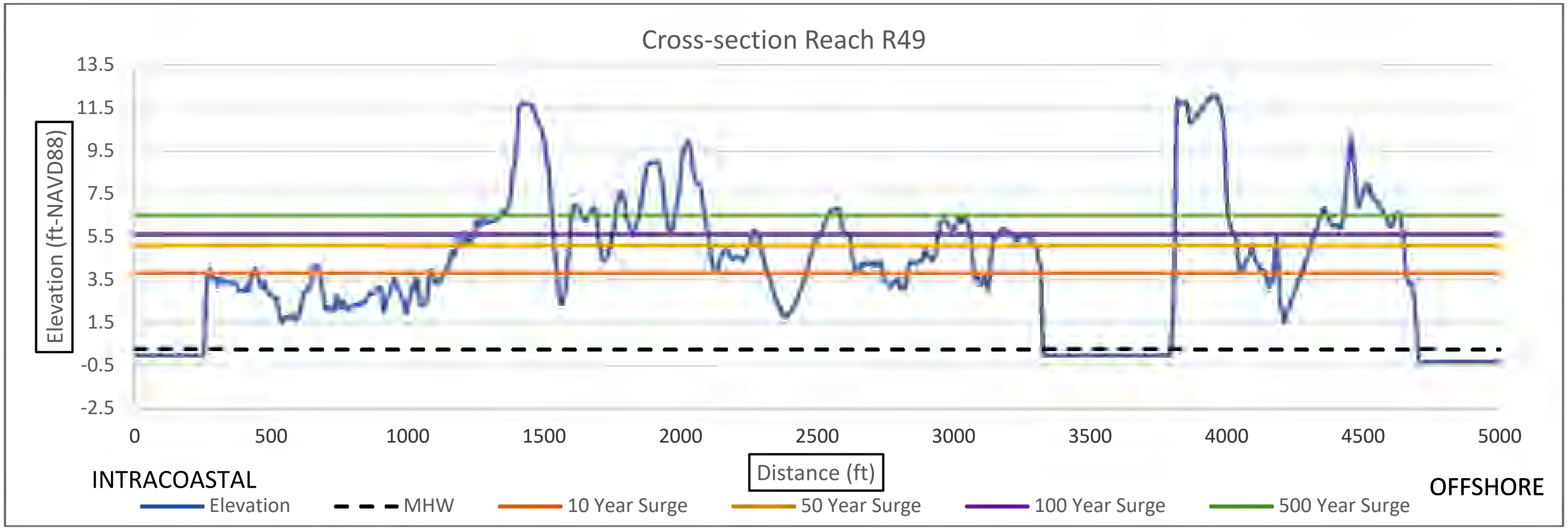
Cross-section Reach R45.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
1500
2000
2500
3000
3500
4000
4500
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R46
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

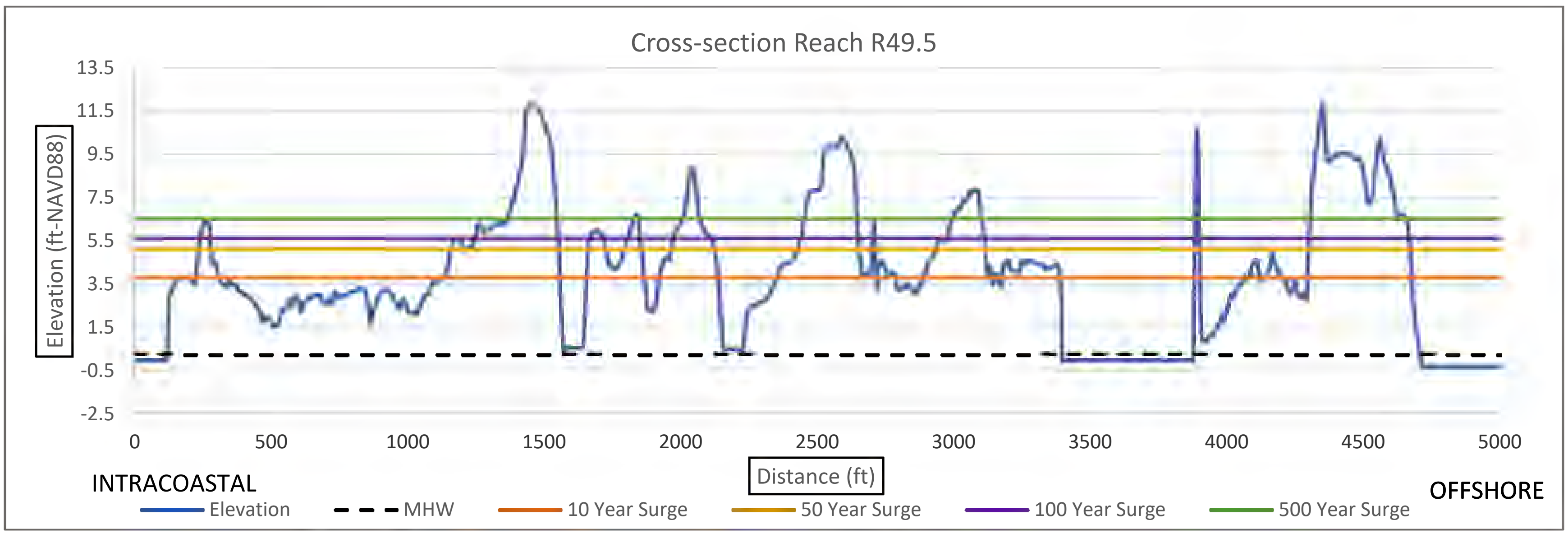

Cross-section Reach R46.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
1000
2000
3000
4000
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R47
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

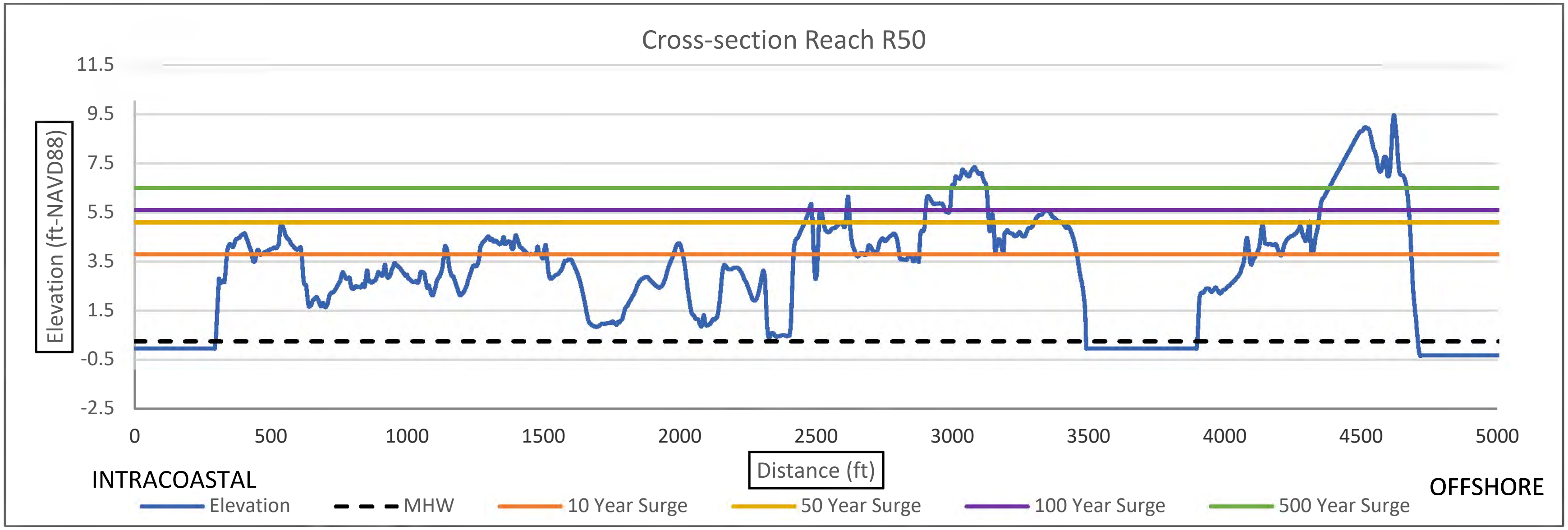

Cross-section Reach R48
Elevation (ft-NAVD88)
17.5
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



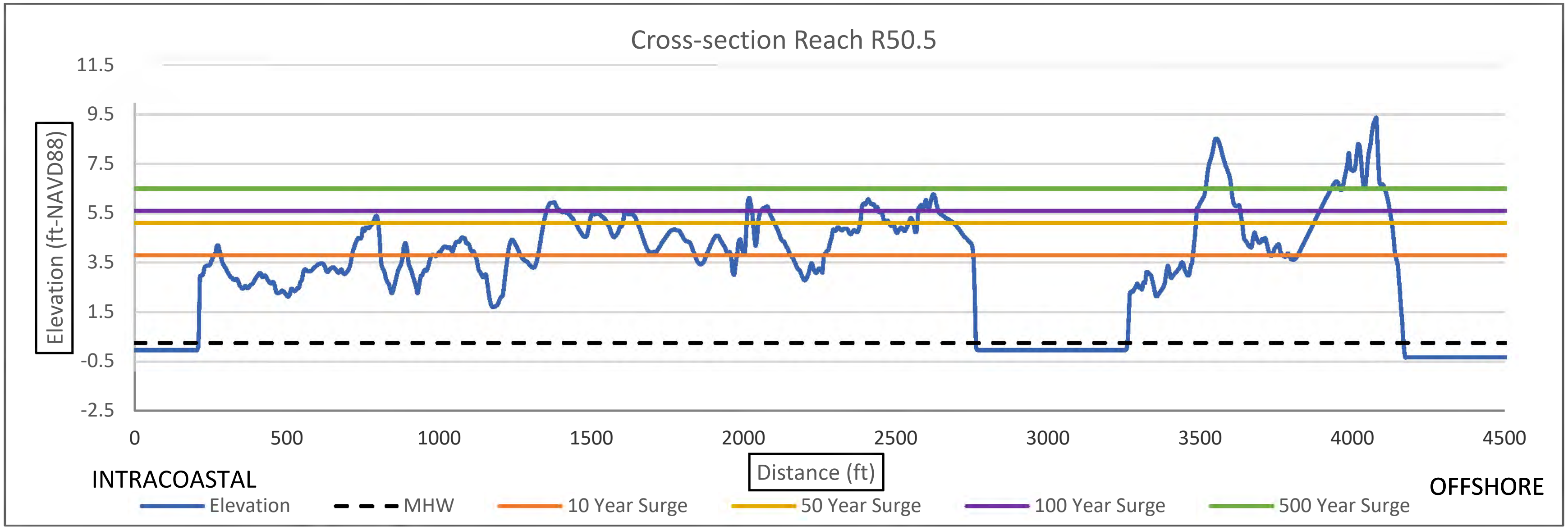
Cross-section Reach R49
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



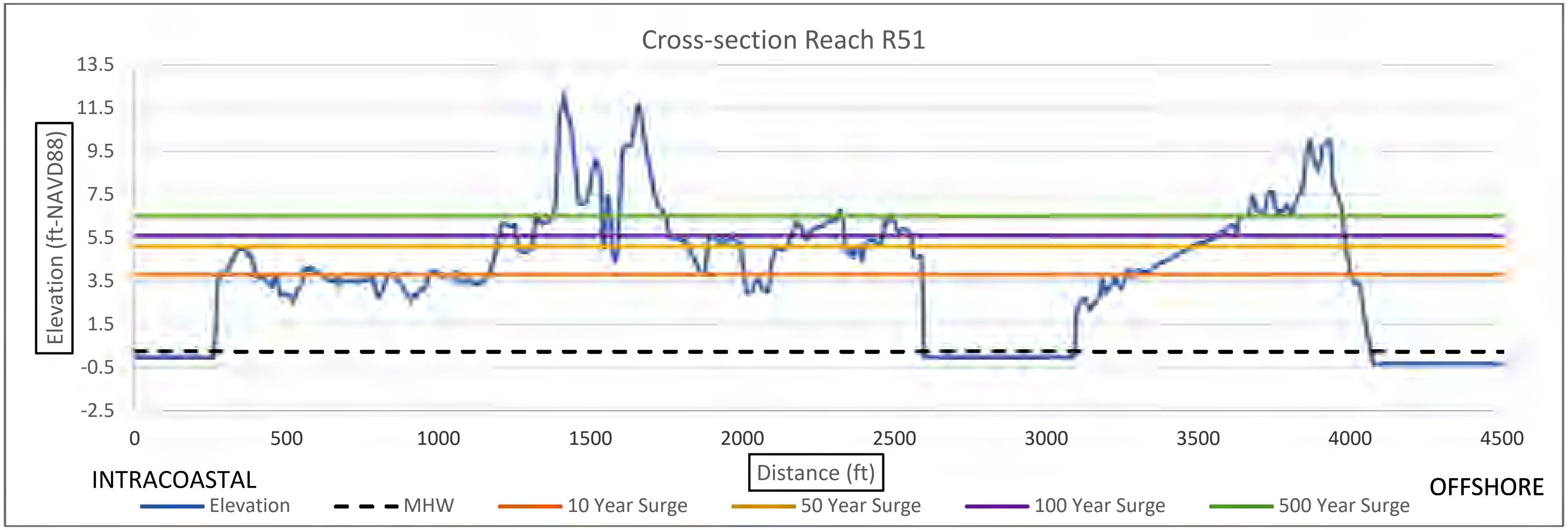
Cross-section Reach R49.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

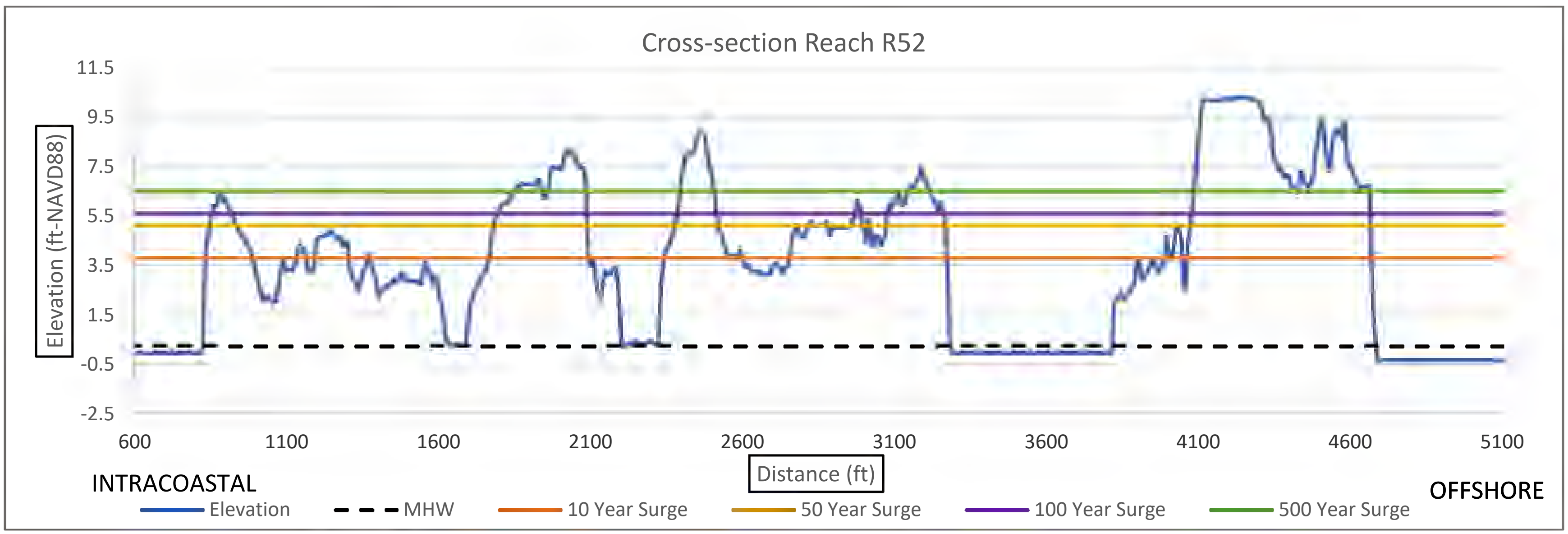


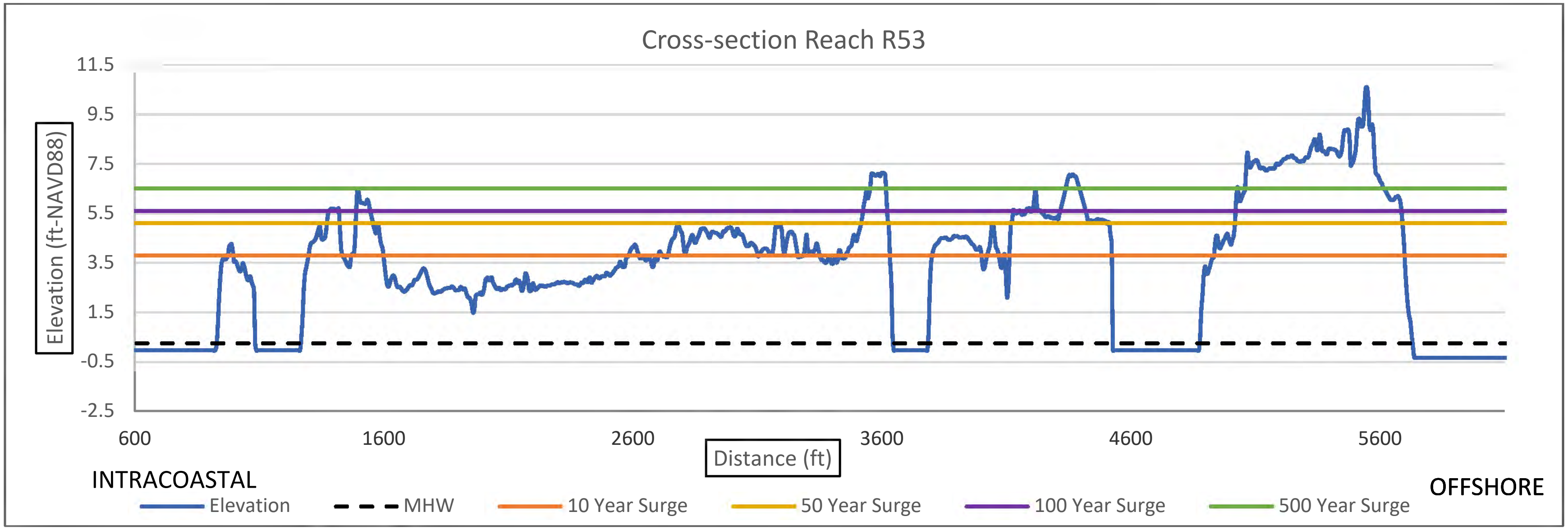
Cross-section Reach R50
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

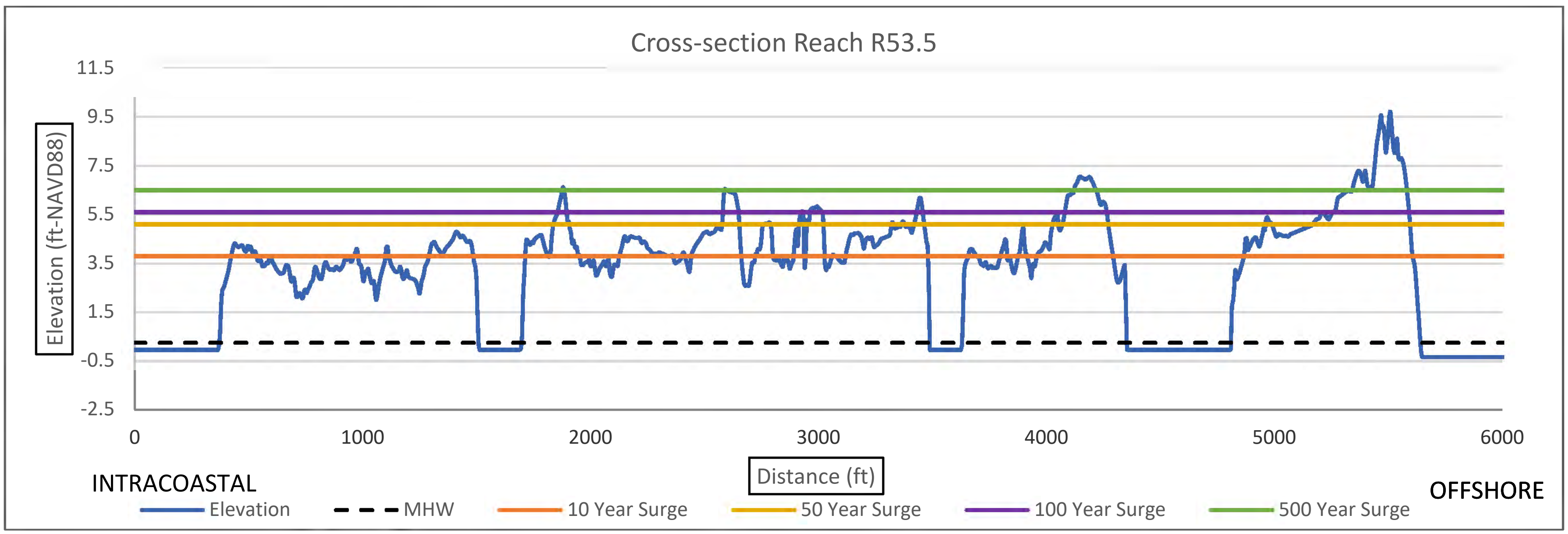


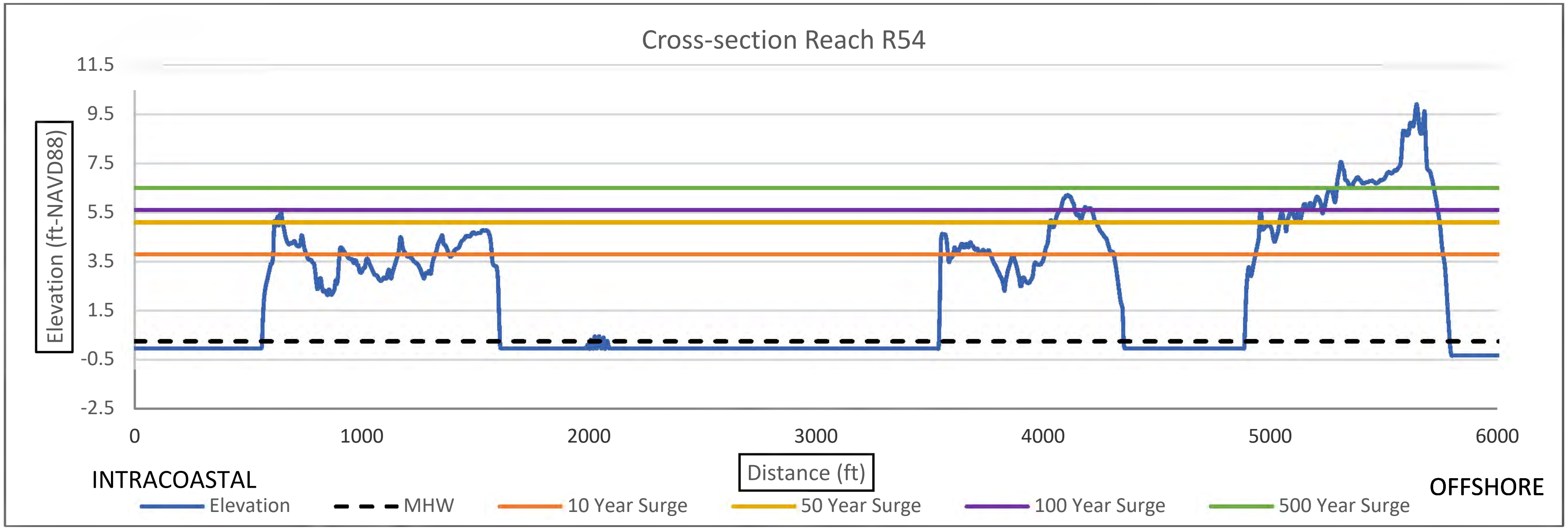
Cross-section Reach R50.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

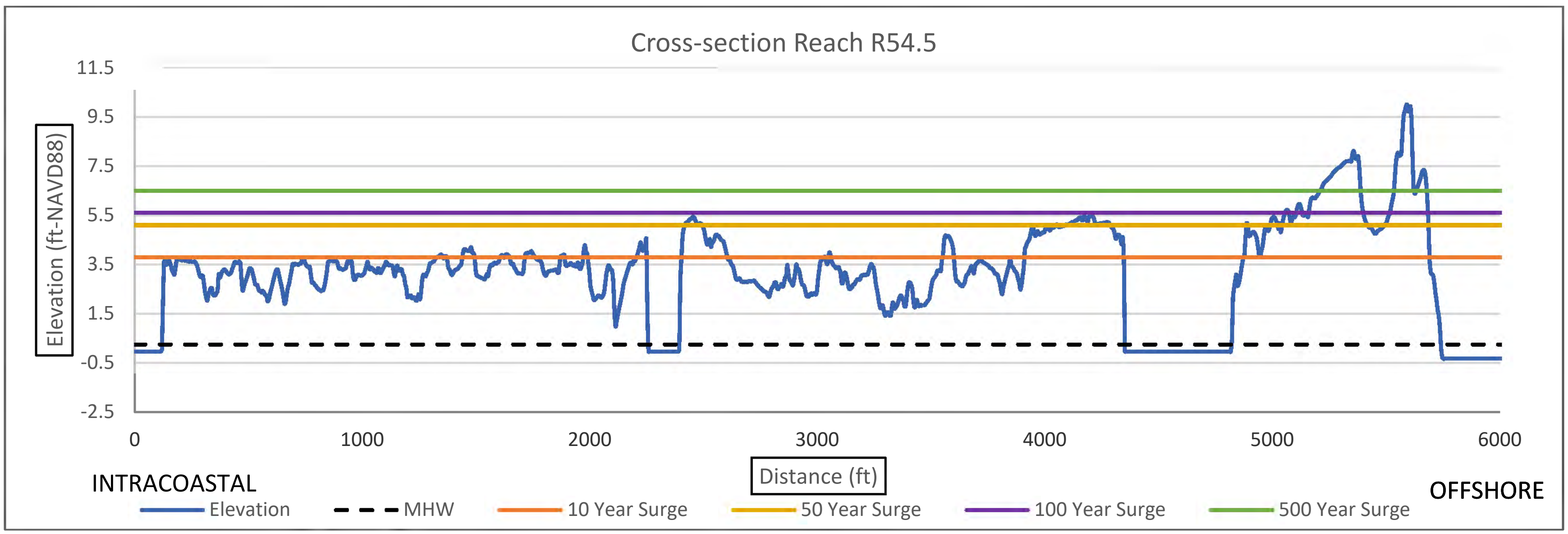

Cross-section Reach R51
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

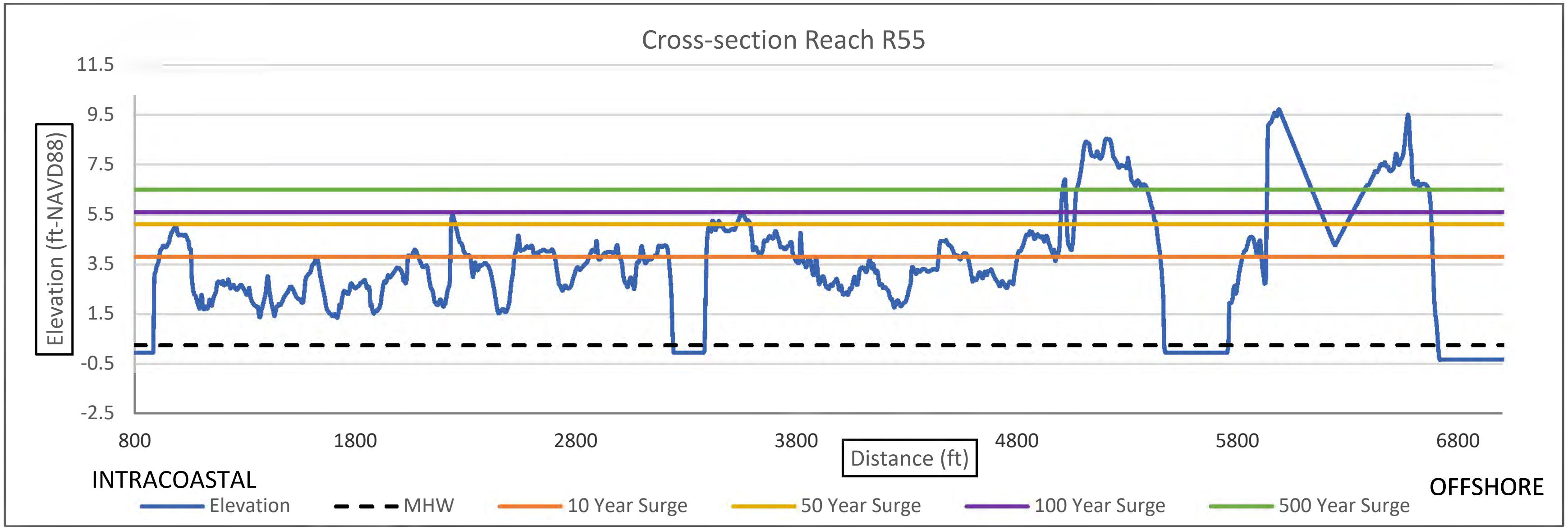

Cross-section Reach R52
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
600
1100
1600
2100
2600
3100
3600
4100
4600
5100
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

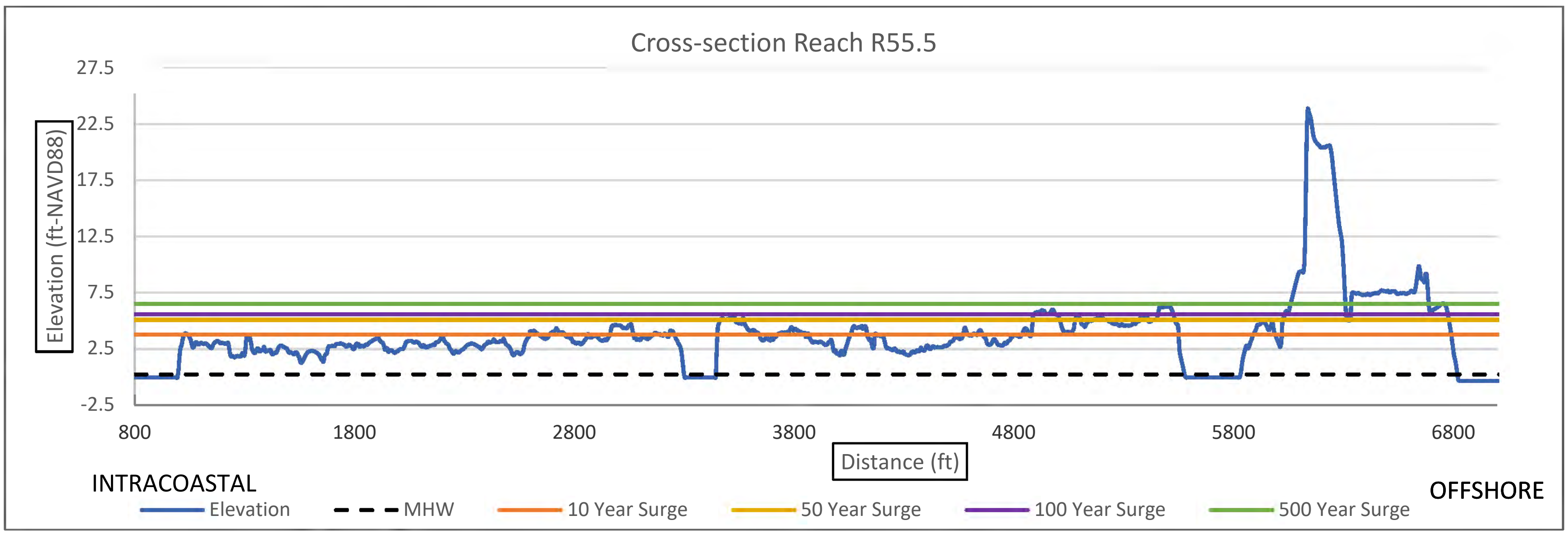

Cross-section Reach R53
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
600
1600
2600
3600
4600
5600
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

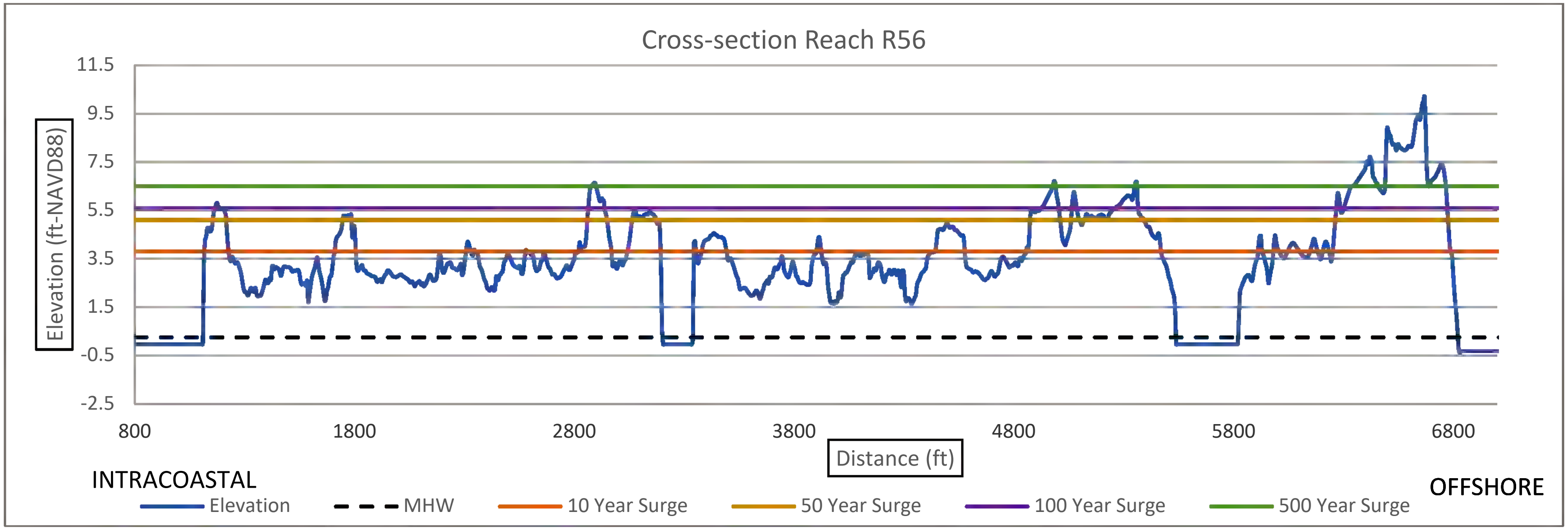

Cross-section Reach R53.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
1000
2000
3000
4000
5000
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

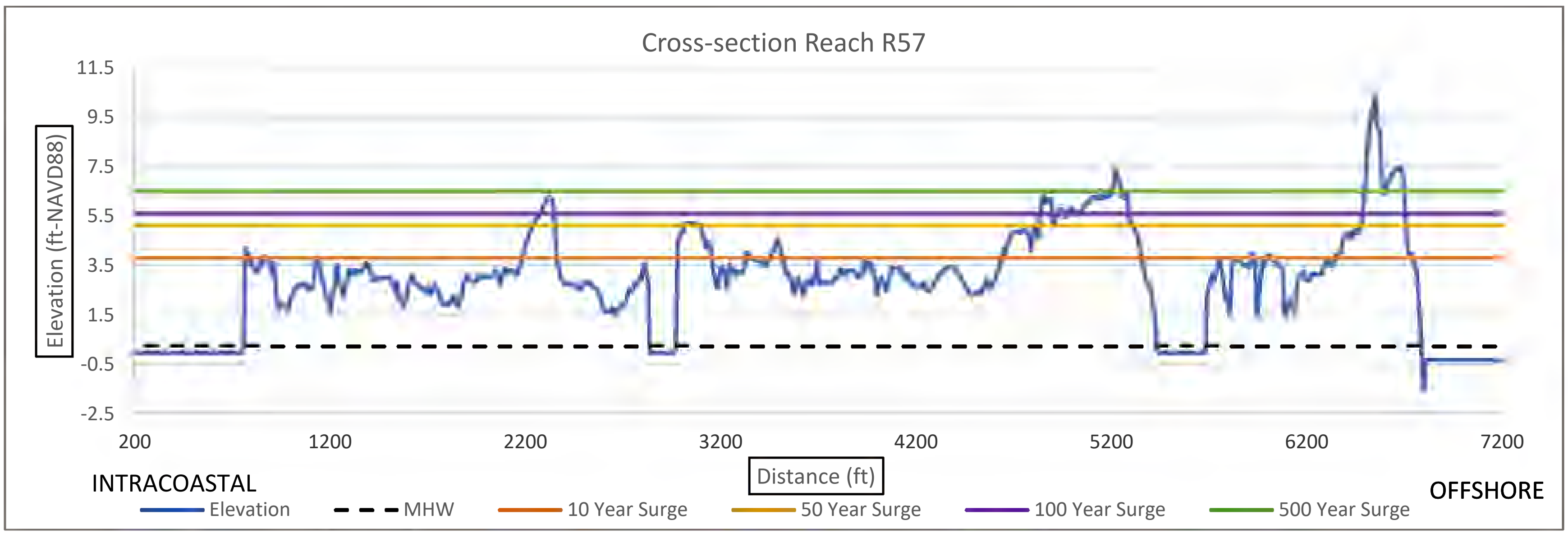

Cross-section Reach R54
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

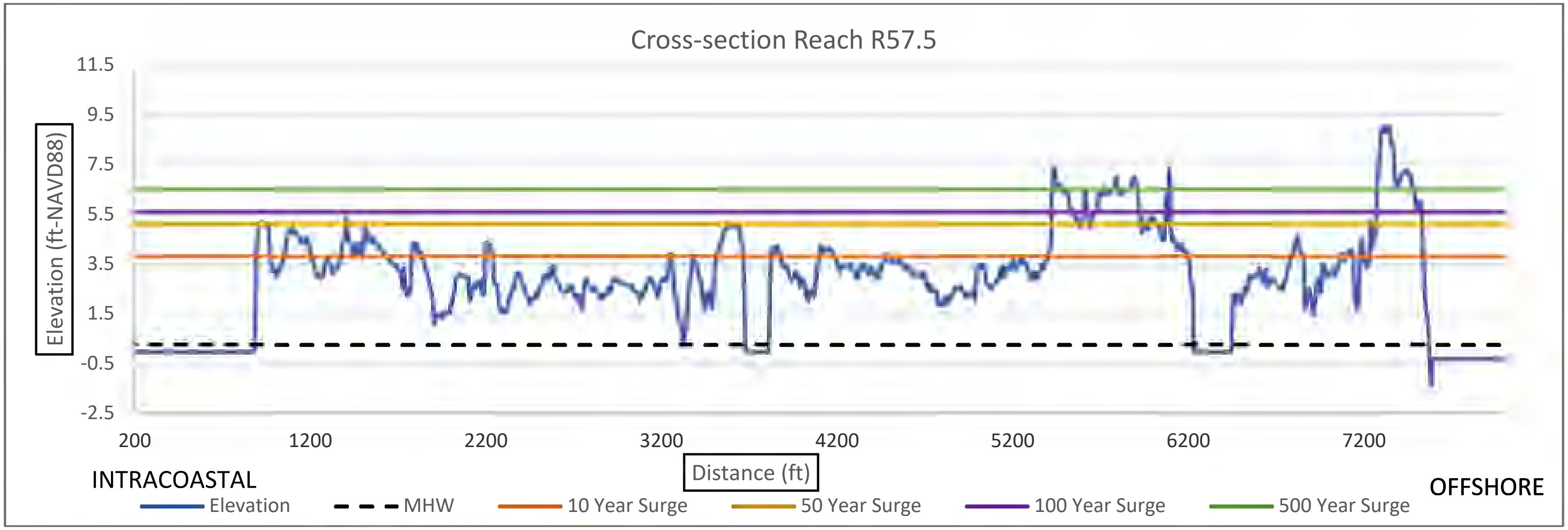

Cross-section Reach R54.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

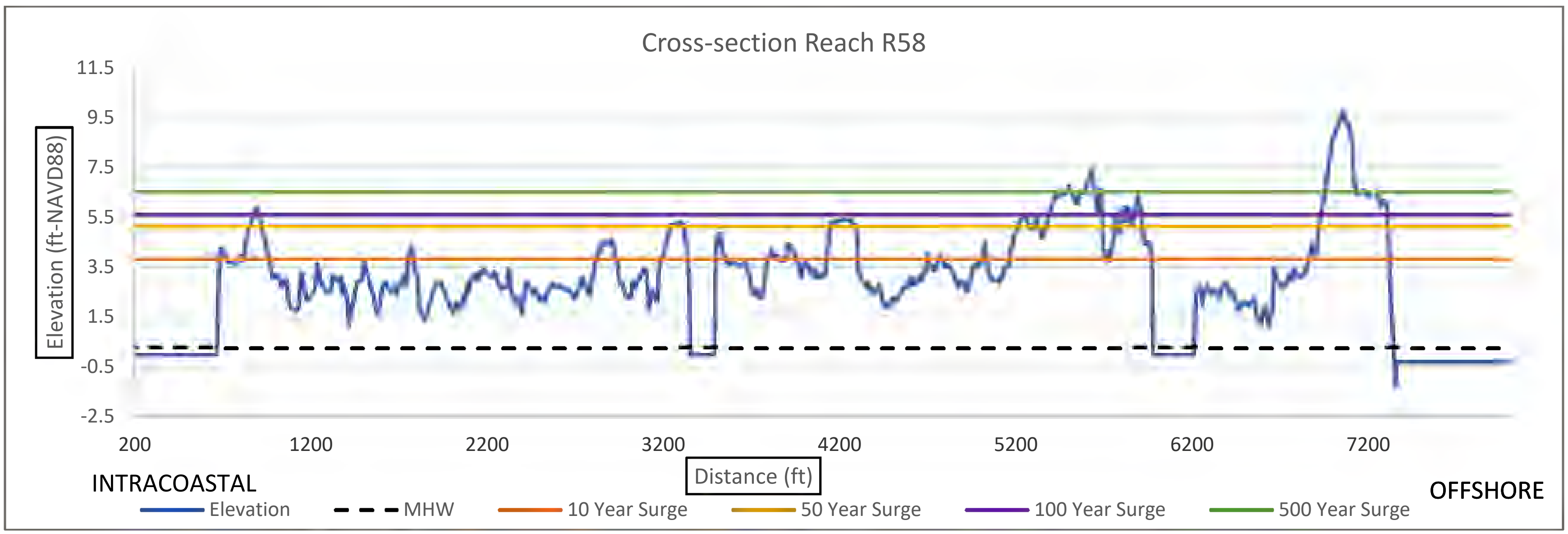

Cross-section Reach R55
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
800
1800
2800
3800
4800
5800
6800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

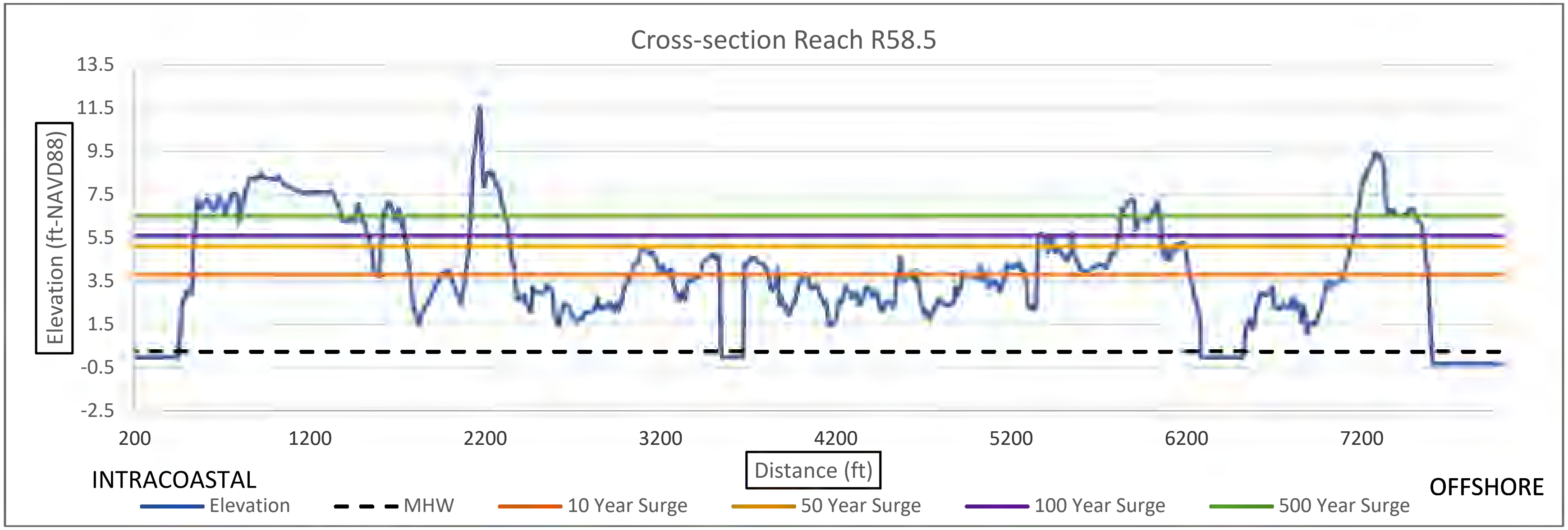

Cross-section Reach R55.5
27.5
22.5
17.5
12.5
7.5
2.5
-2.5
Elevation (ft-NAVD88)
800
1800
2800
3800
4800
5800
6800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

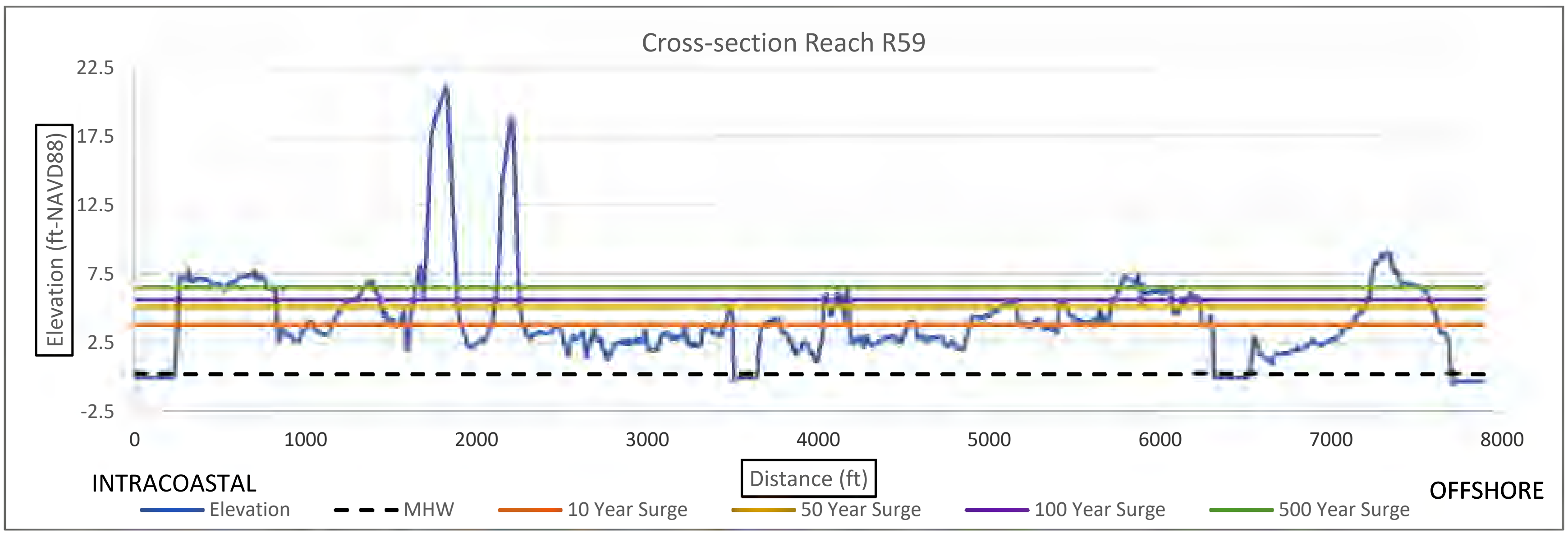

Cross-section Reach R56
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
800
1800
2800
3800
4800
5800
6800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

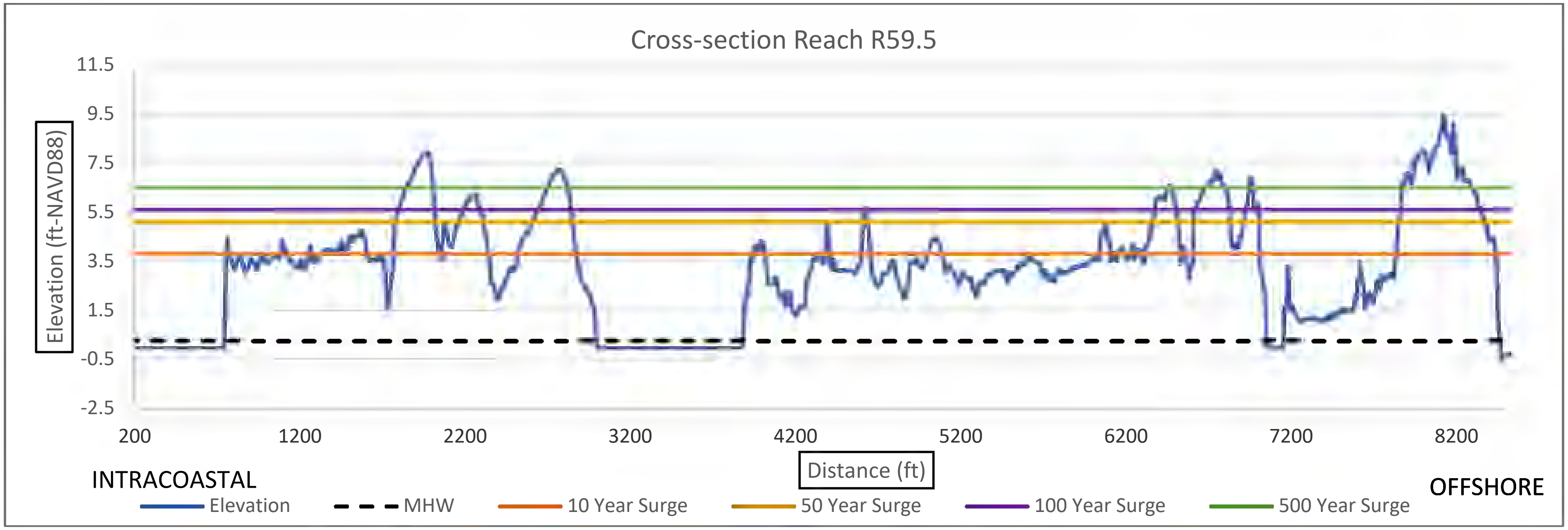

Cross-section Reach R57
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
6200
7200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

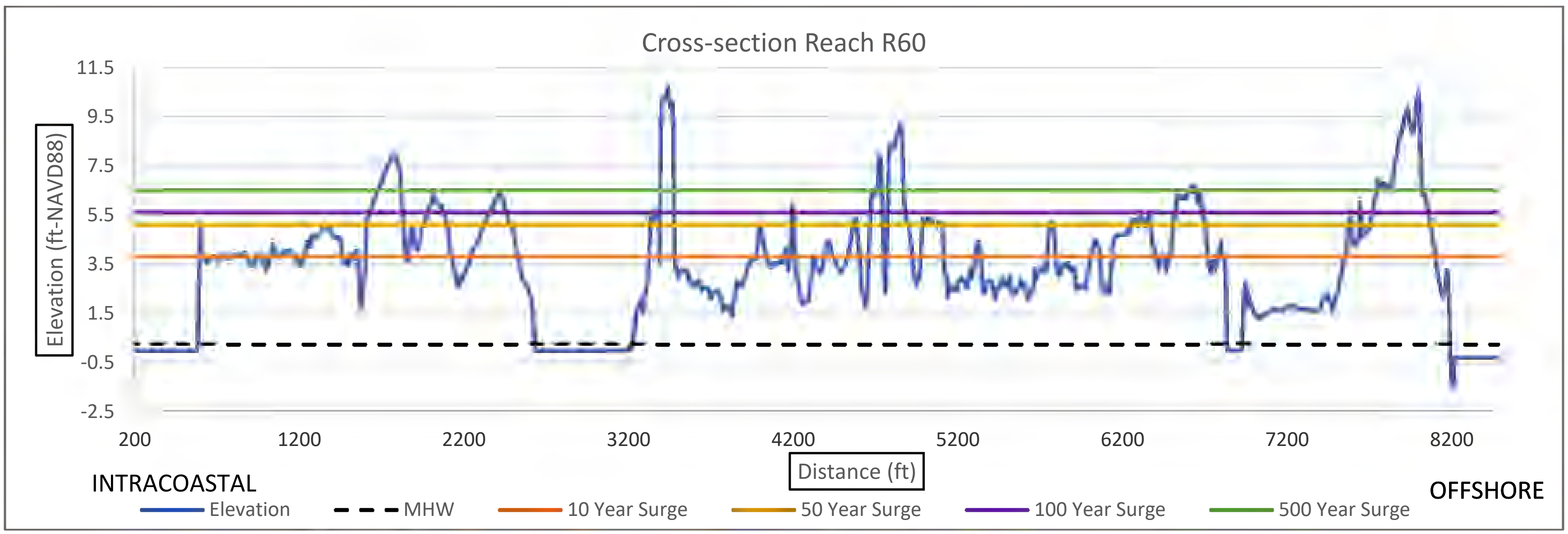

Cross-section Reach R57.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
6200
7200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

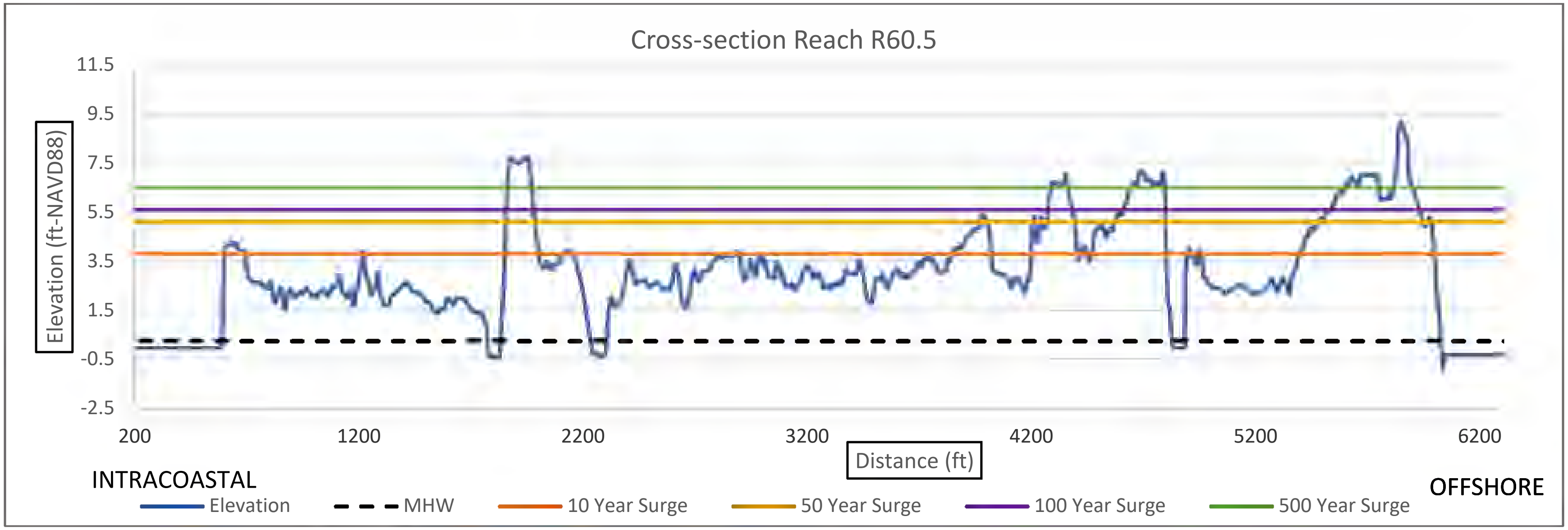

Cross-section Reach R58
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
6200
7200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R58.5
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
200
1200
2200
3200
4200
5200
6200
7200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

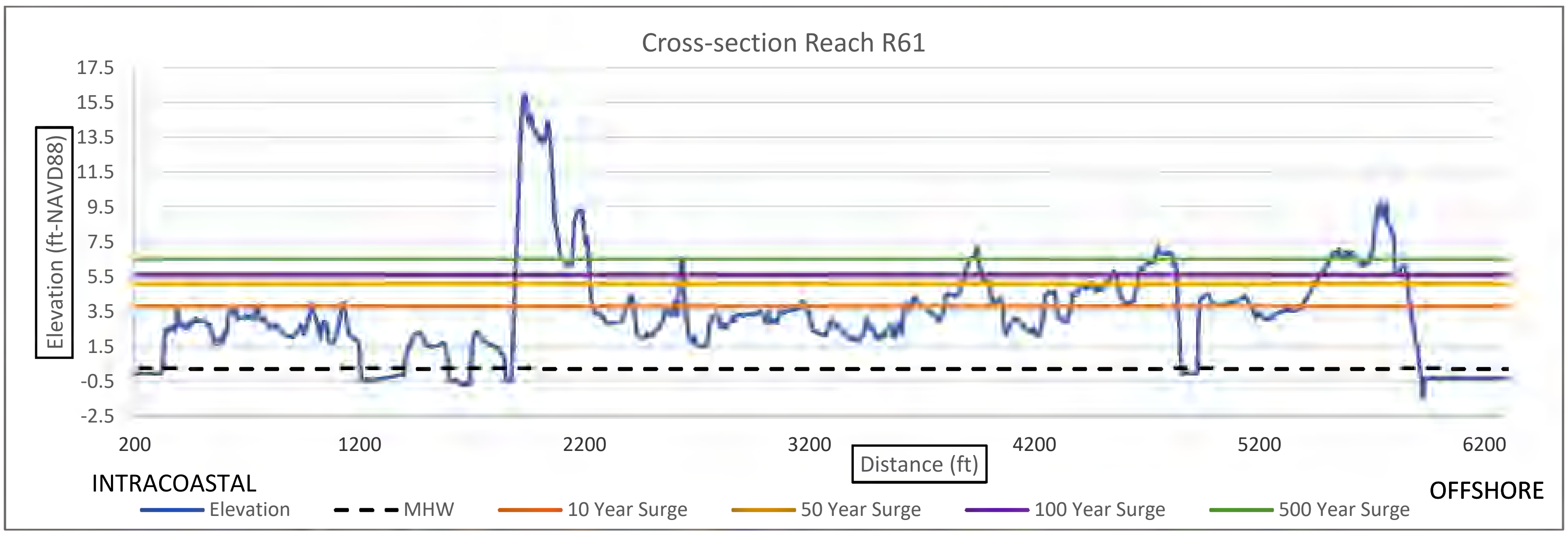

Cross-section Reach R59
Elevation (ft-NAVD88)
22.5
17.5
12.5
7.5
2.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R59.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
200
1200
2200
3200
4200
5200
6200
7200
8200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

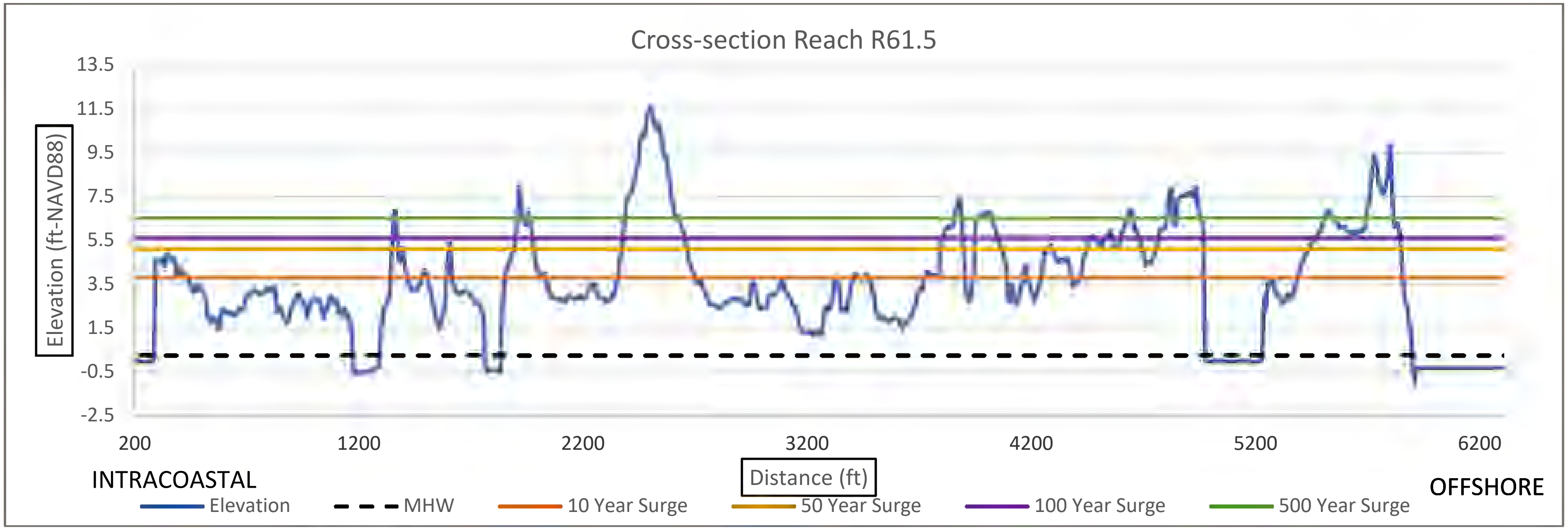

Cross-section Reach R60
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
200
1200
2200
3200
4200
5200
6200
7200
8200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

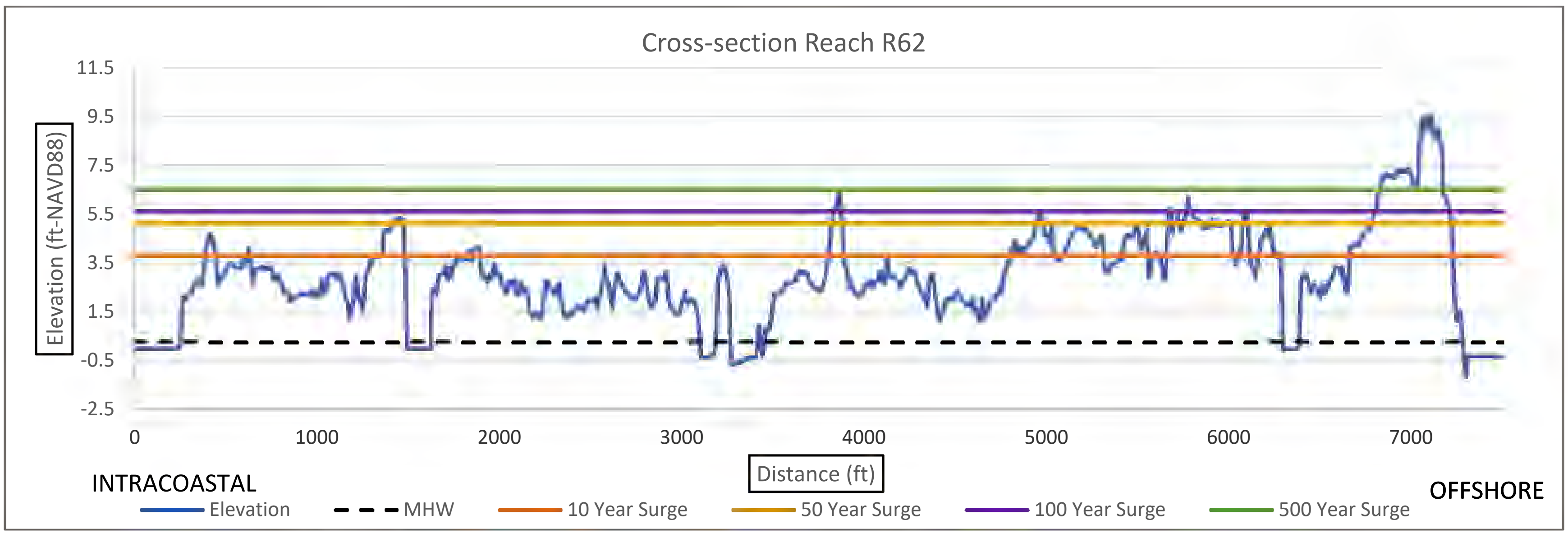


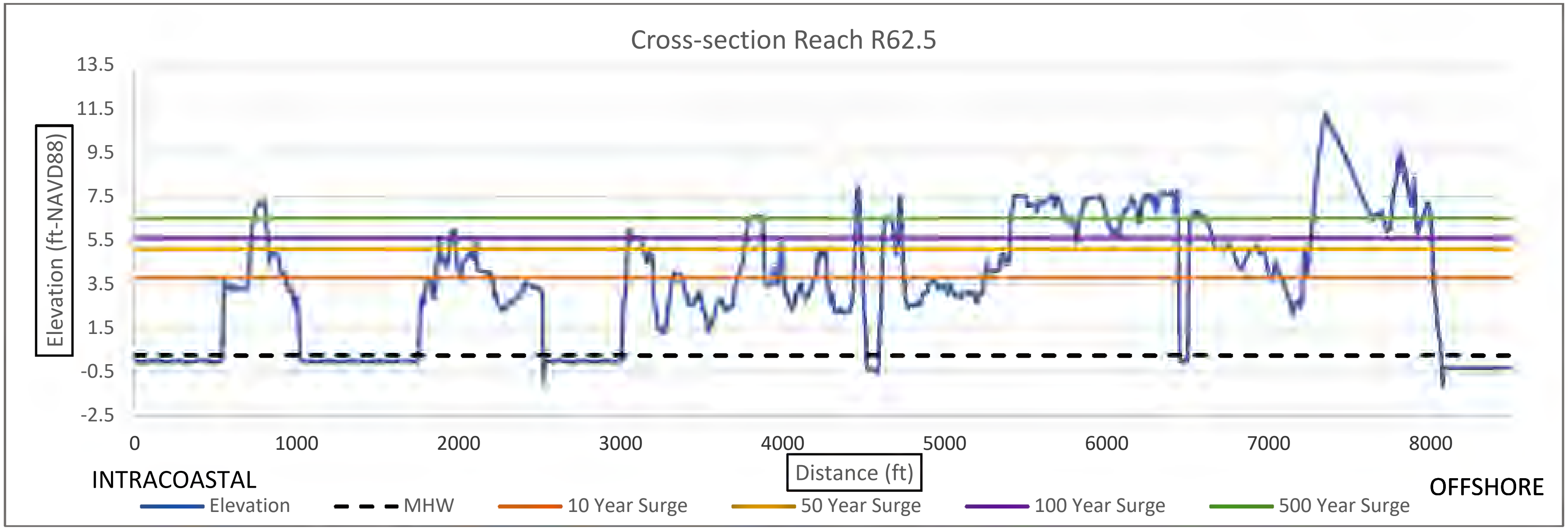
Cross-section Reach R60.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
6200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

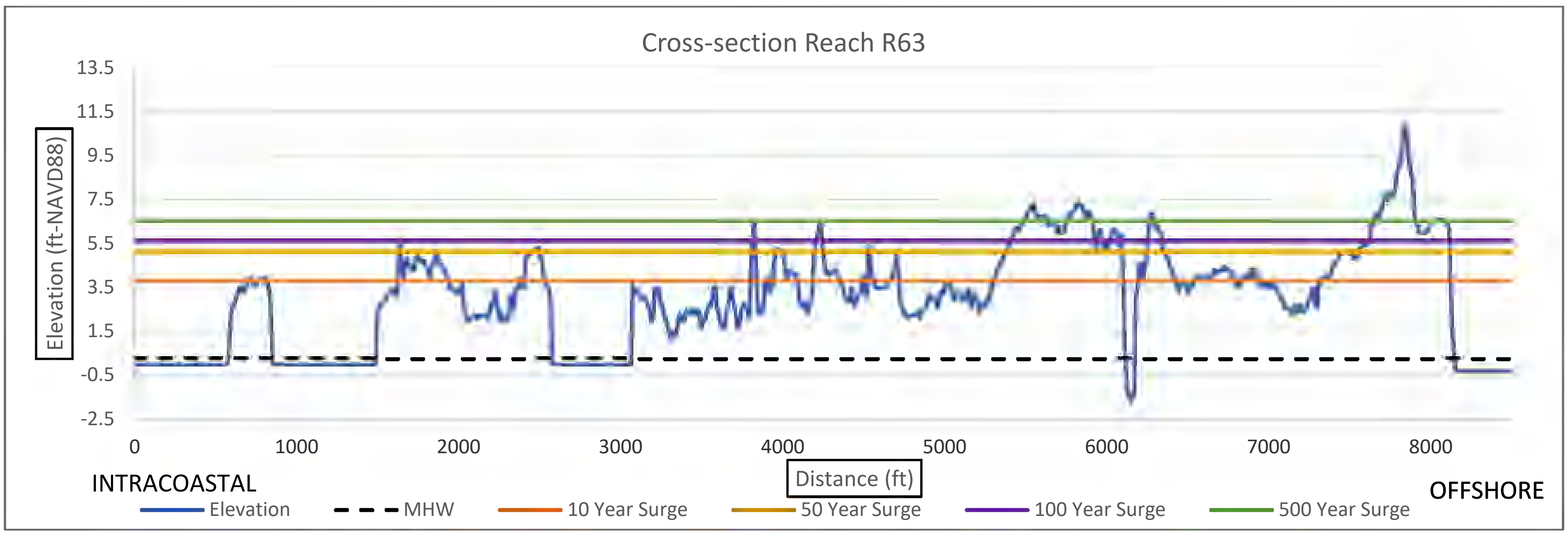


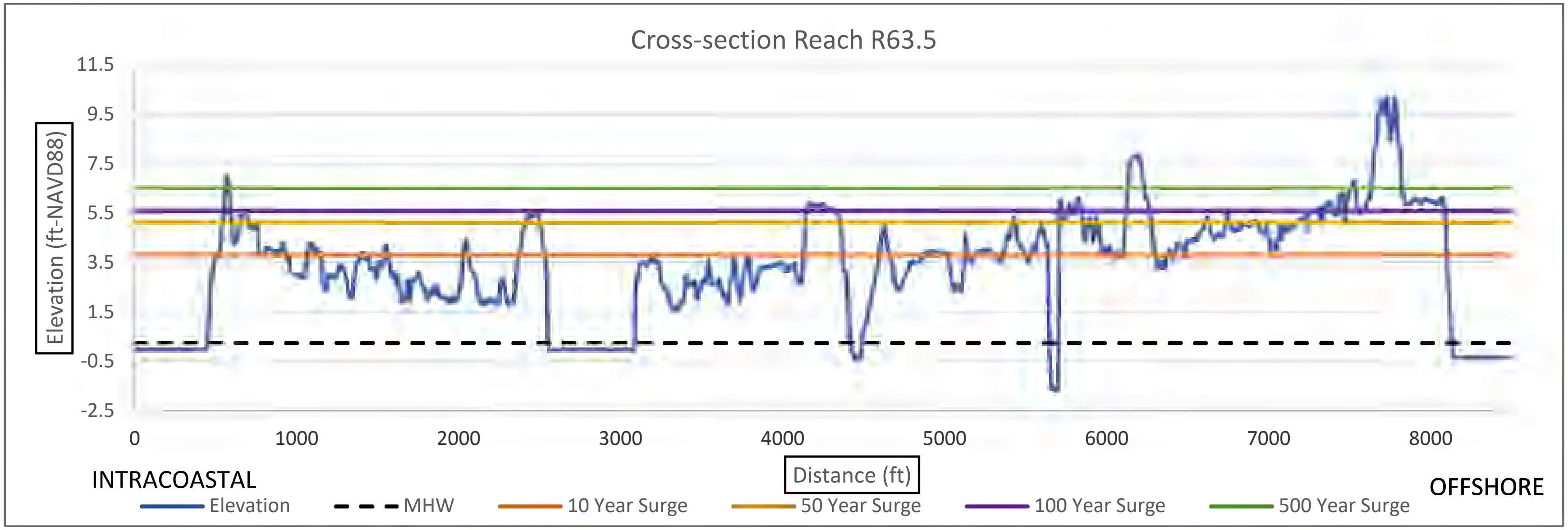
Cross-section Reach R61
17.5
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
6200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R61.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
200
1200
2200
3200
4200
5200
6200
INTRACOASTAL
Distance (ft)
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

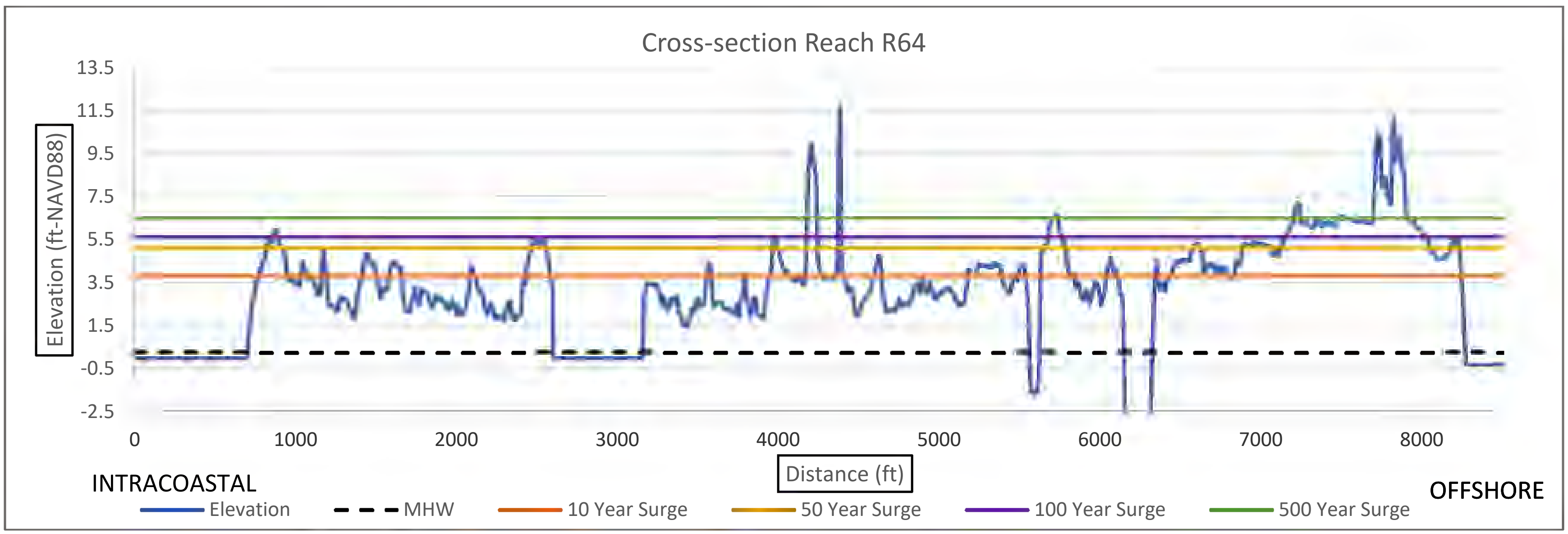

Cross-section Reach R62
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
1000
2000
3000
4000
5000
6000
7000
INTRACOASTAL
Distance (ft)
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R62.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

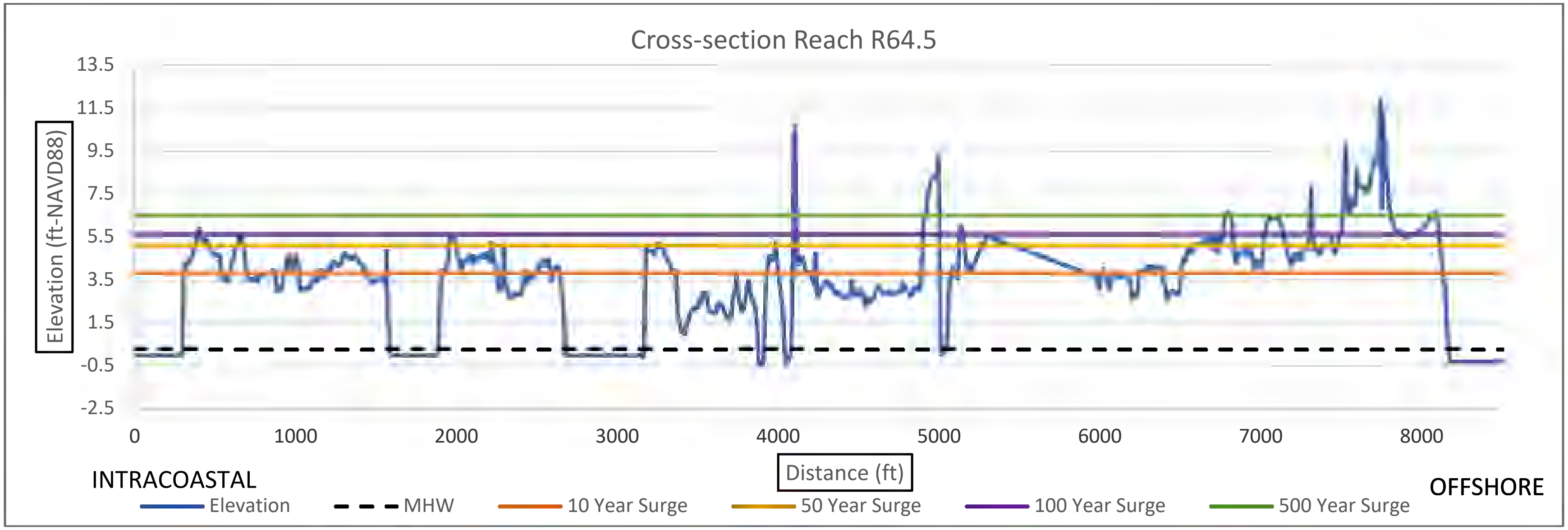

Cross-section Reach R63
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



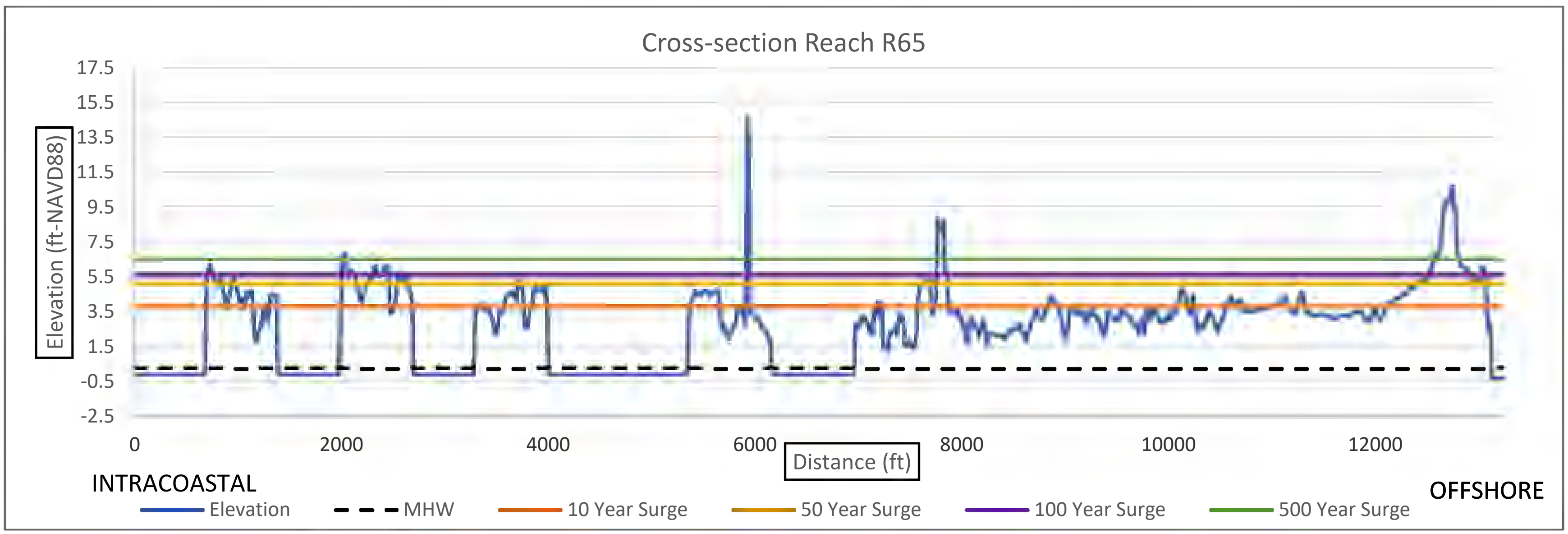
Cross-section Reach R63.5
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



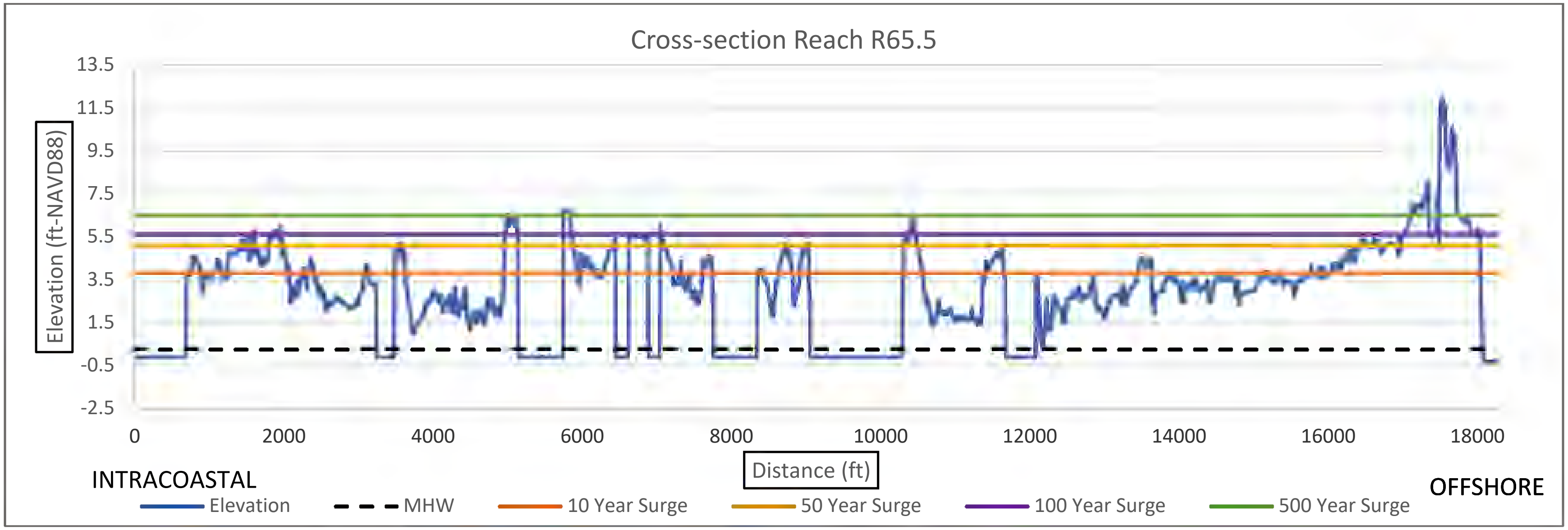
Cross-section Reach R64
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R64.5
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R65
Elevation (ft-NAVD88)
17.5
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
2000
4000
6000
8000
10000
12000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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11.5
9.5
7.5
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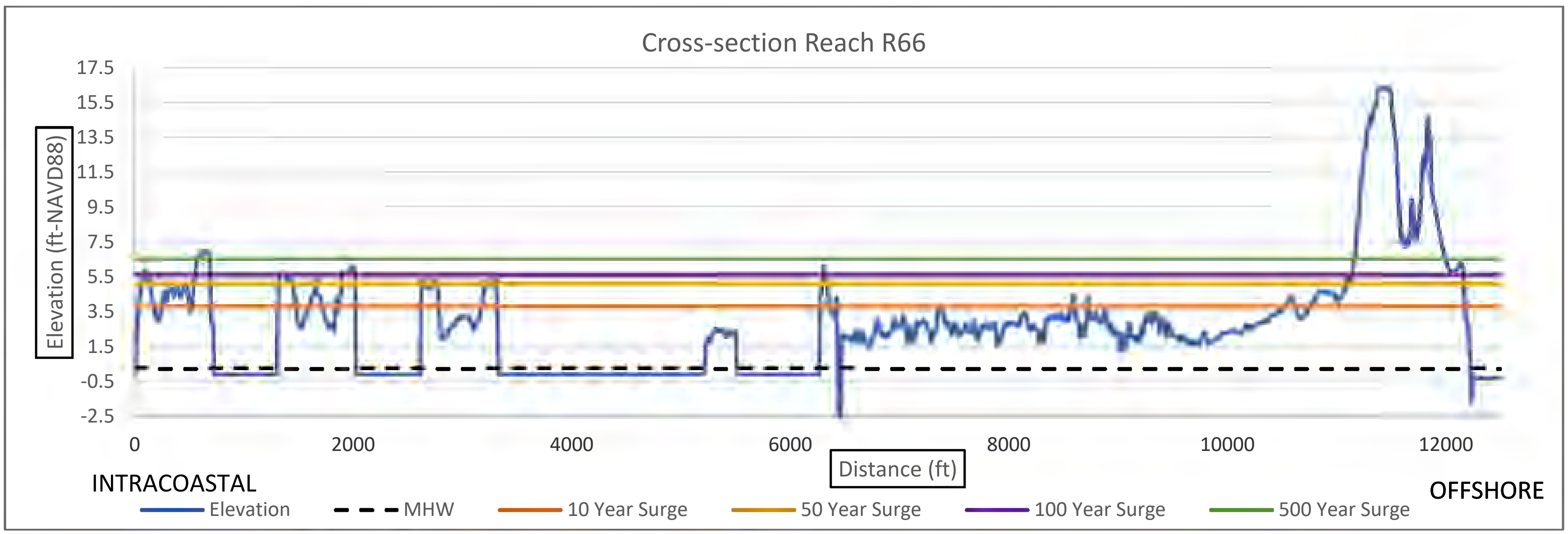
-2.5
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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7.5
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1.5
-0.5
-2.5
0
2000
4000
6000
8000
10000
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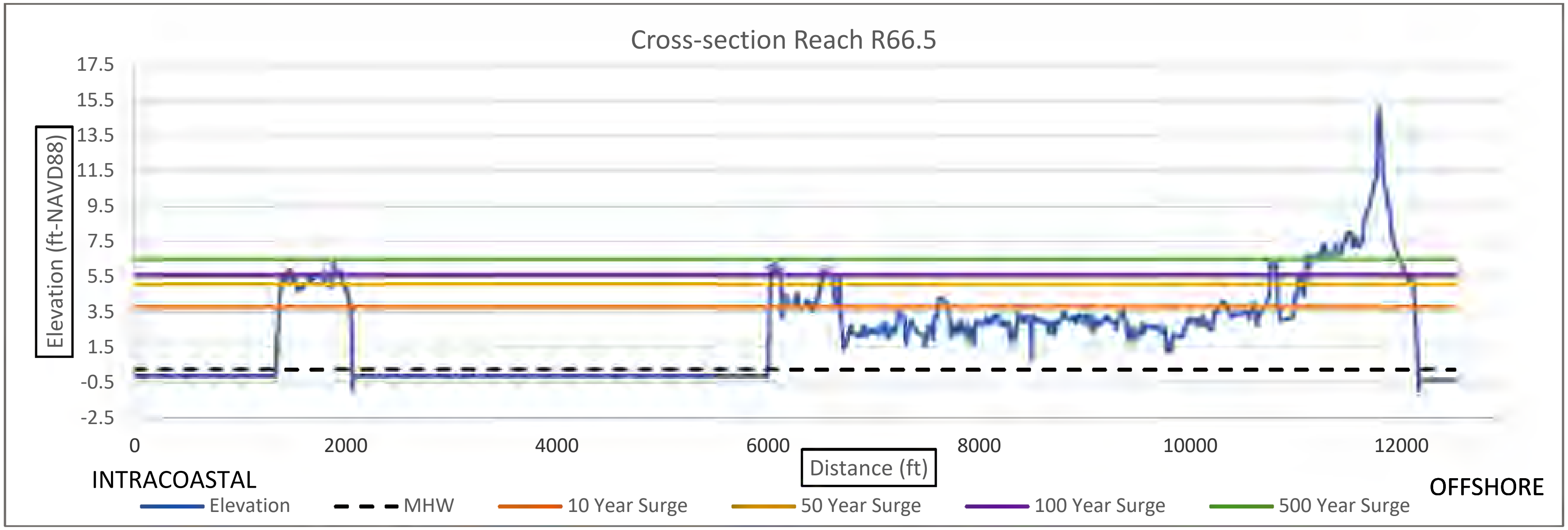
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R66.5
Elevation (ft-NAVD88)
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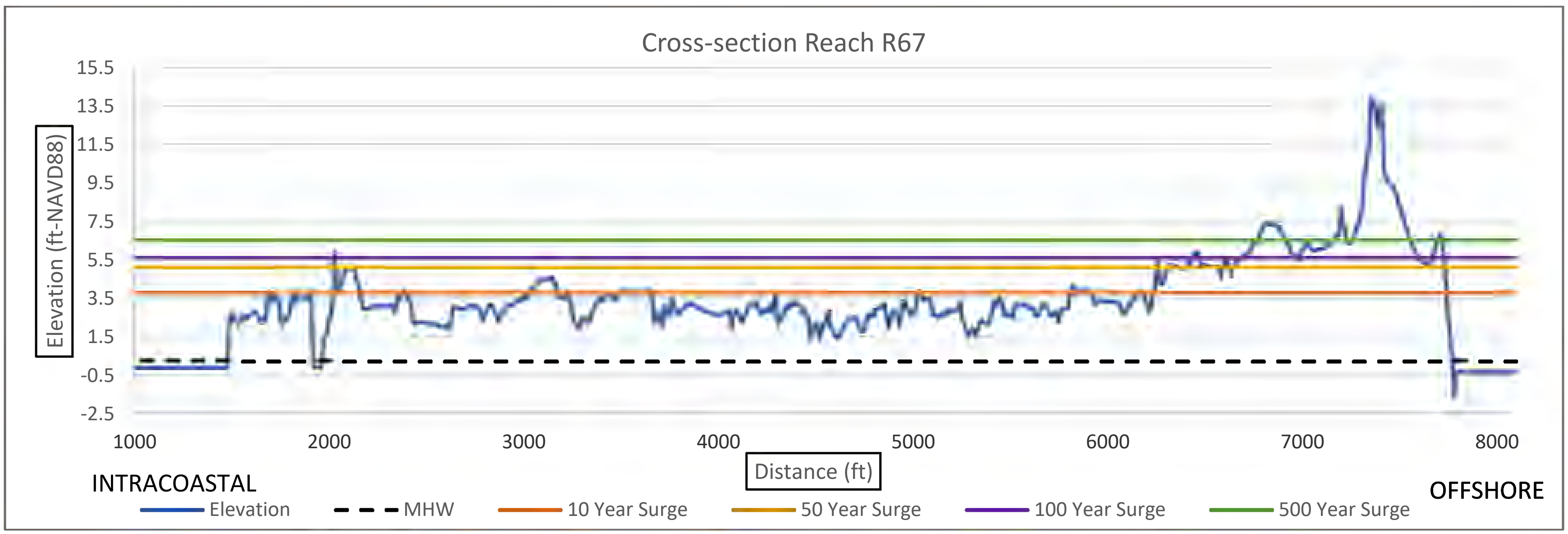
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
2000
4000
6000
8000
10000
12000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



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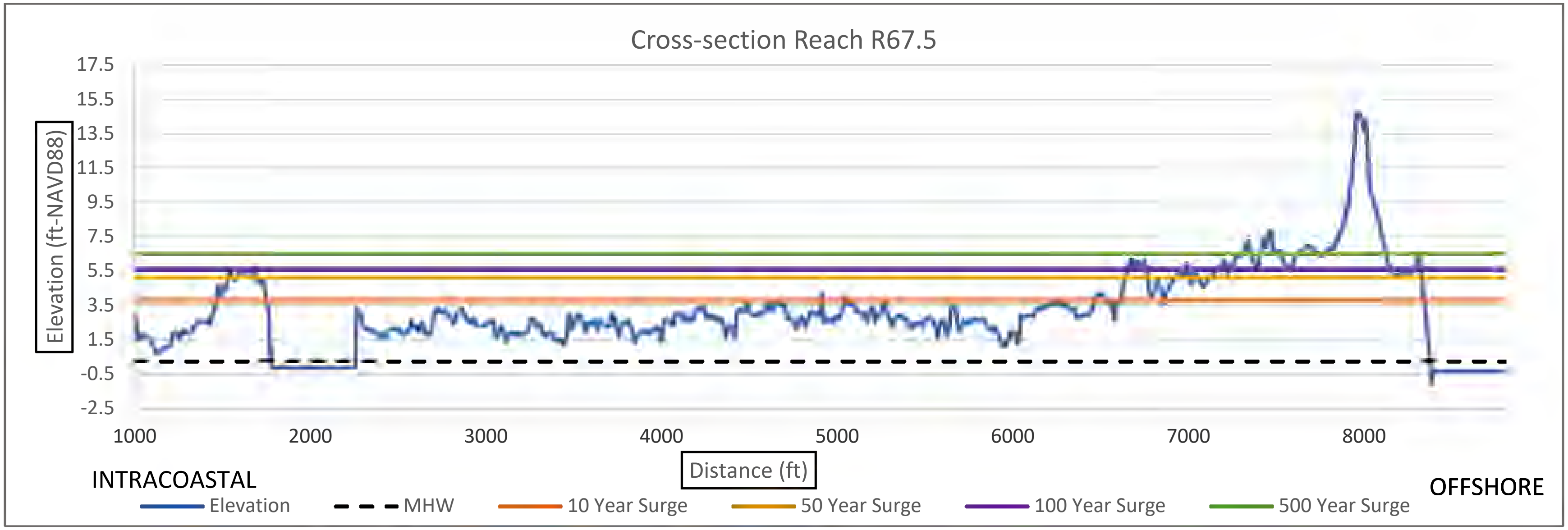
-2.5
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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Elevation (ft-NAVD88)
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11.5
9.5
7.5
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3.5
1.5
-0.5
-2.5
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
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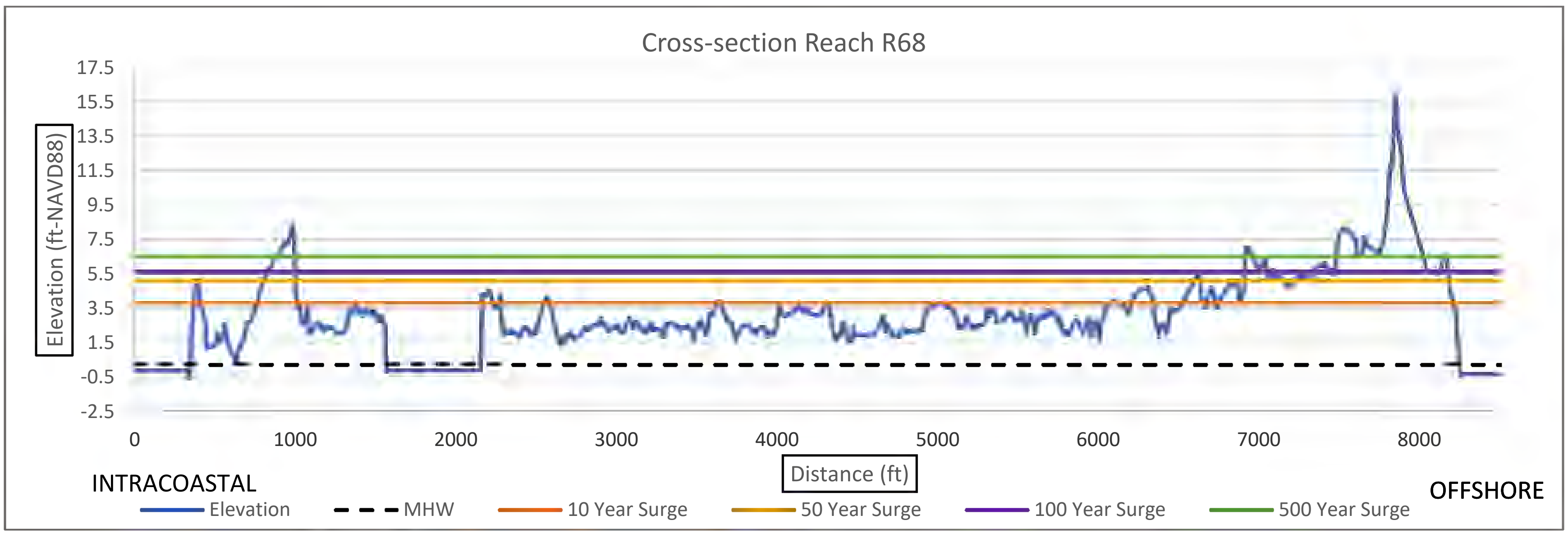
100 Year Surge
500 Year Surge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7.5
5.5
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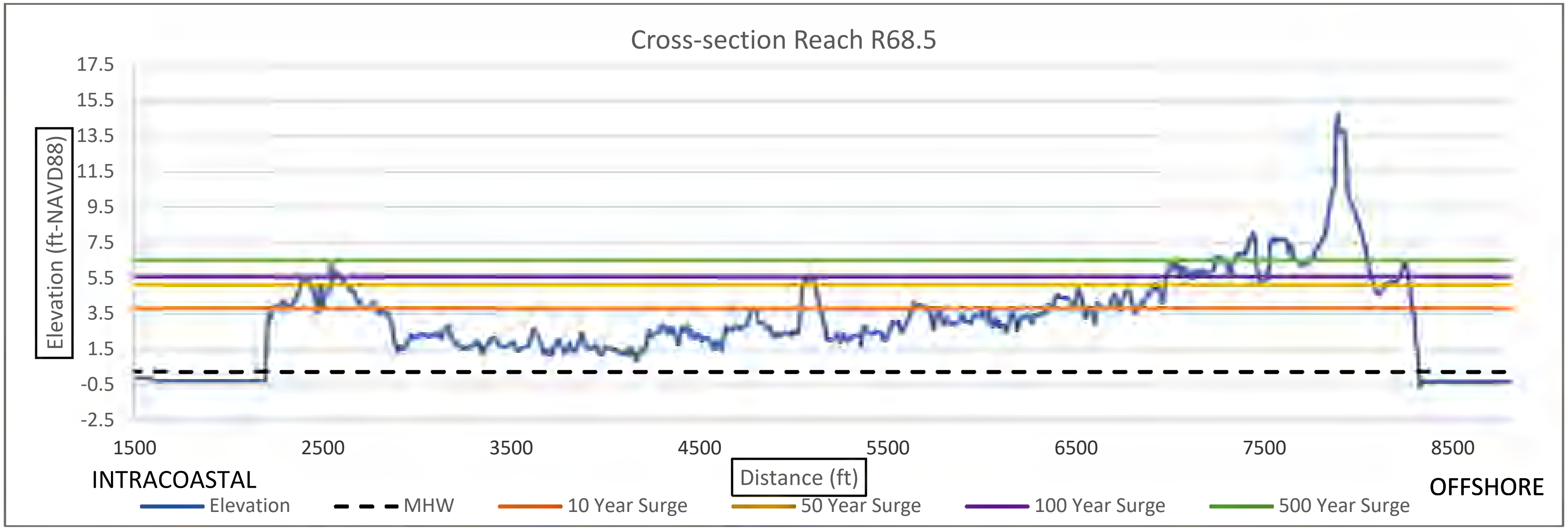
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R68.5
Elevation (ft-NAVD88)
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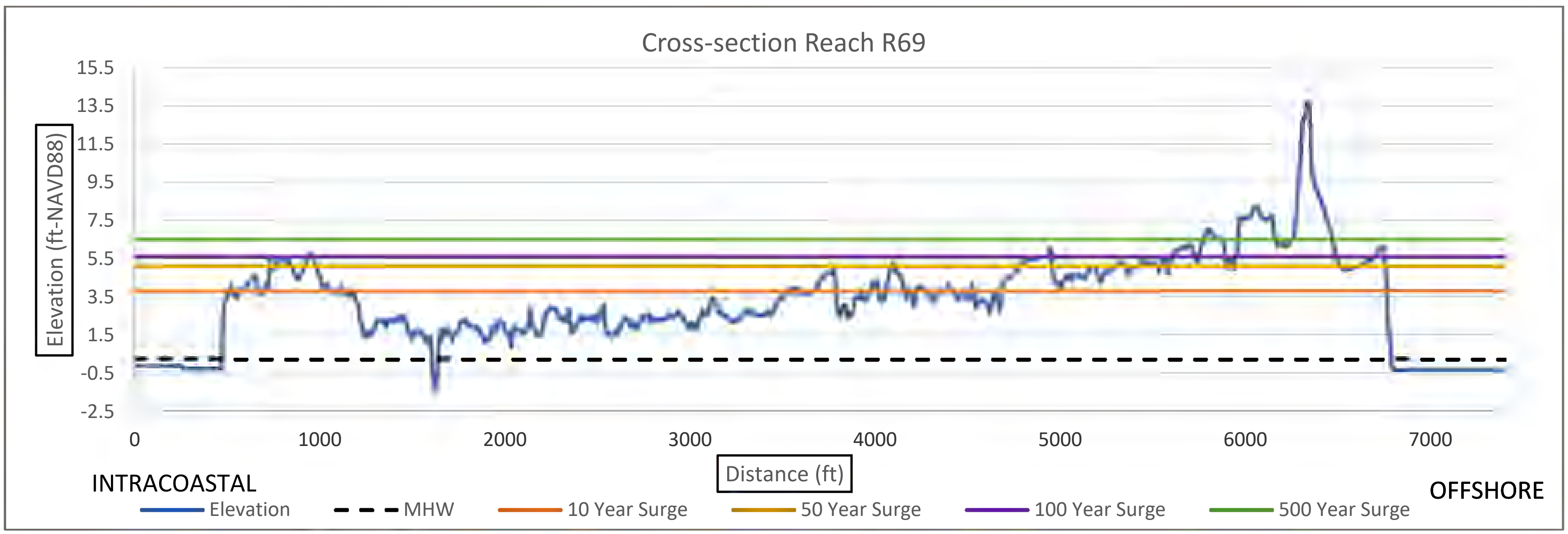
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
1500
2500
3500
4500
5500
6500
7500
8500
INTRACOASTAL
Distance (ft)
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



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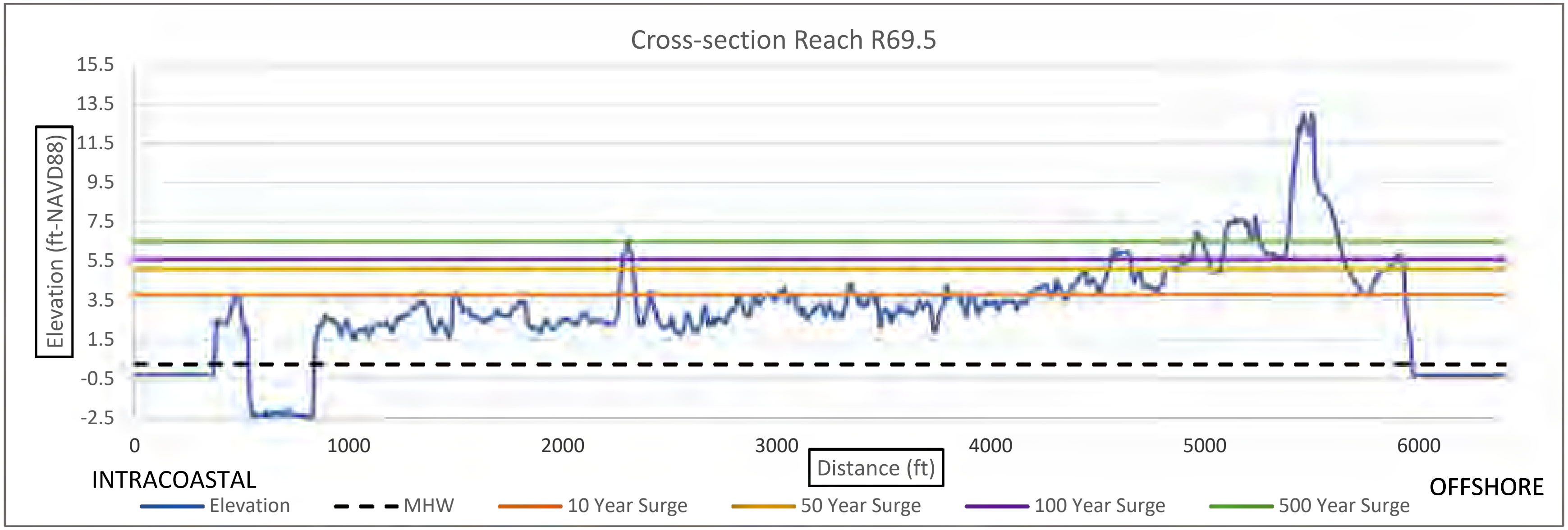
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
INTRACOASTAL
Distance (ft)
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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Elevation (ft-NAVD88)
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1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
Distance (ft)
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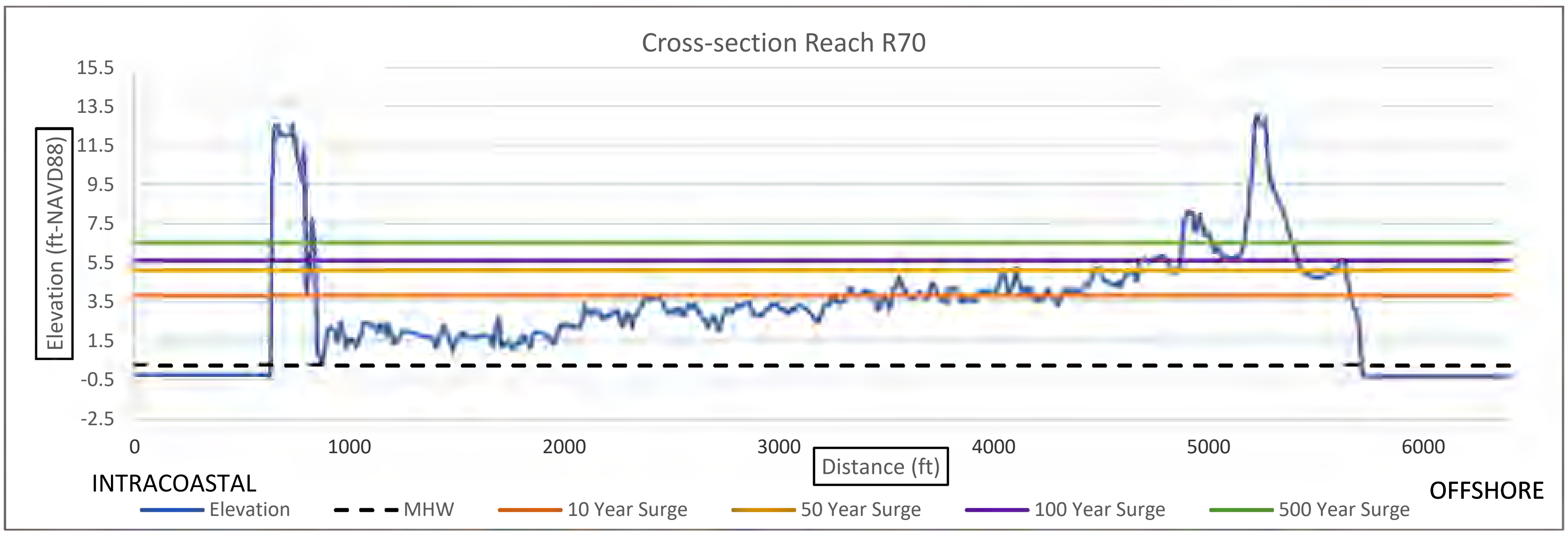
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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Elevation (ft-NAVD88)
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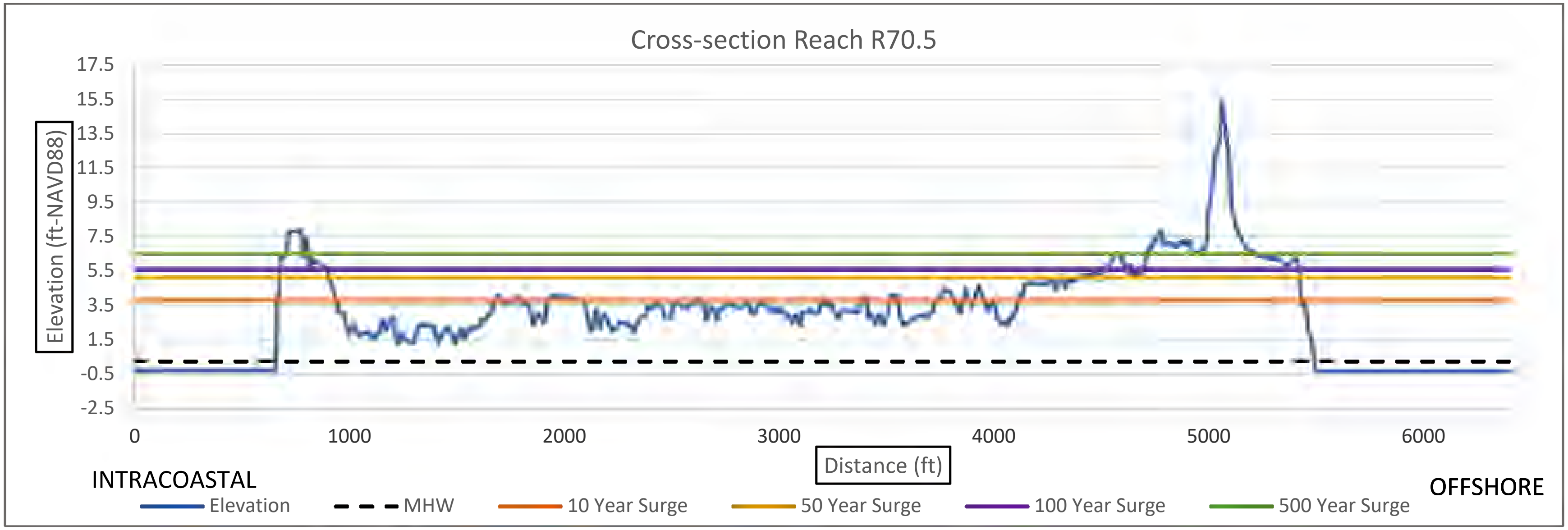
-2.5
0
1000
2000
3000
4000
5000
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R70.5
Elevation (ft-NAVD88)
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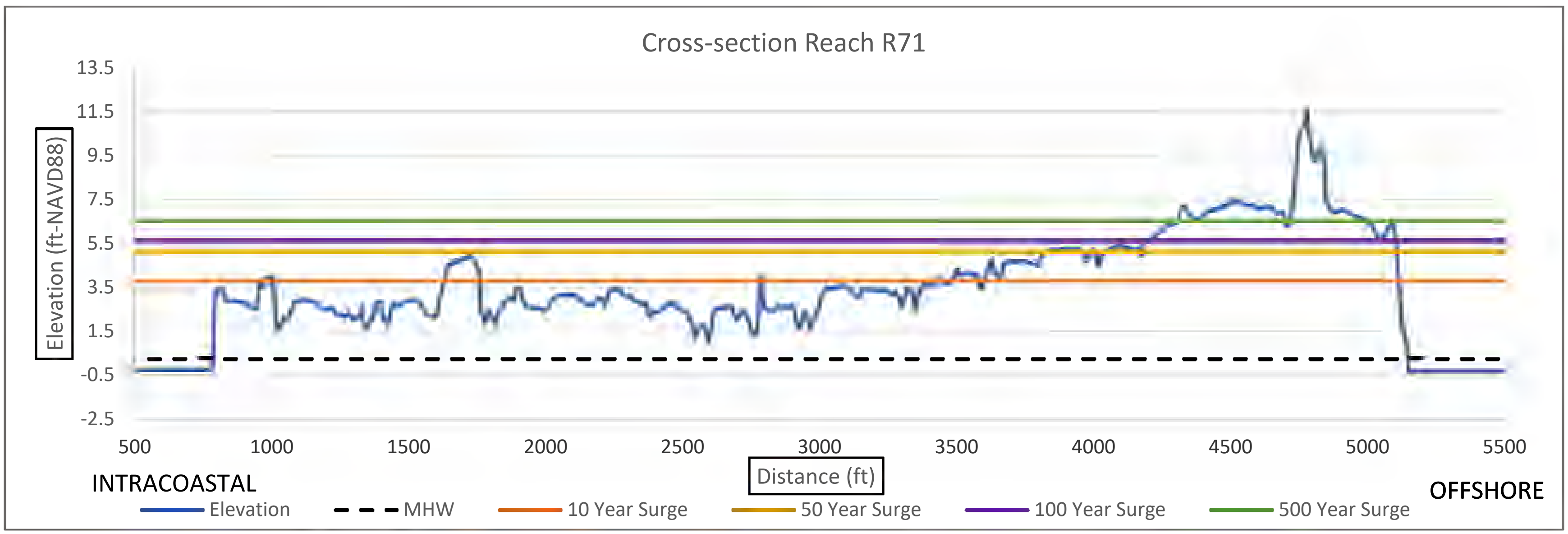
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R71
Elevation (ft-NAVD88)
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7.5
5.5
3.5
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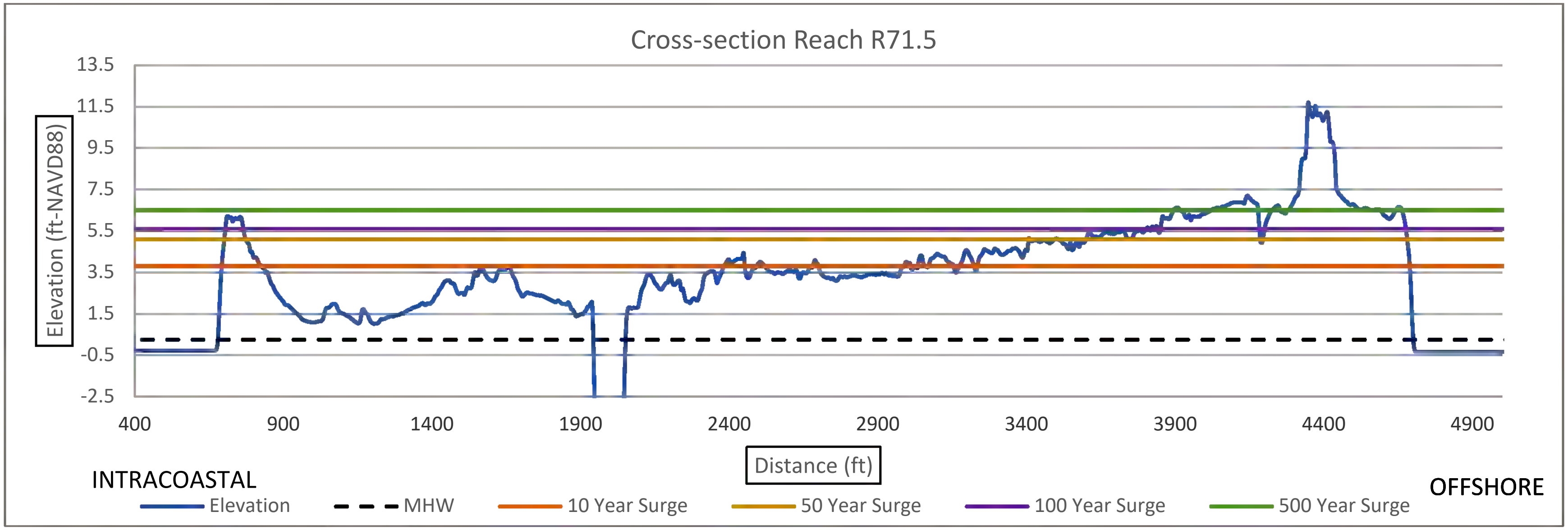
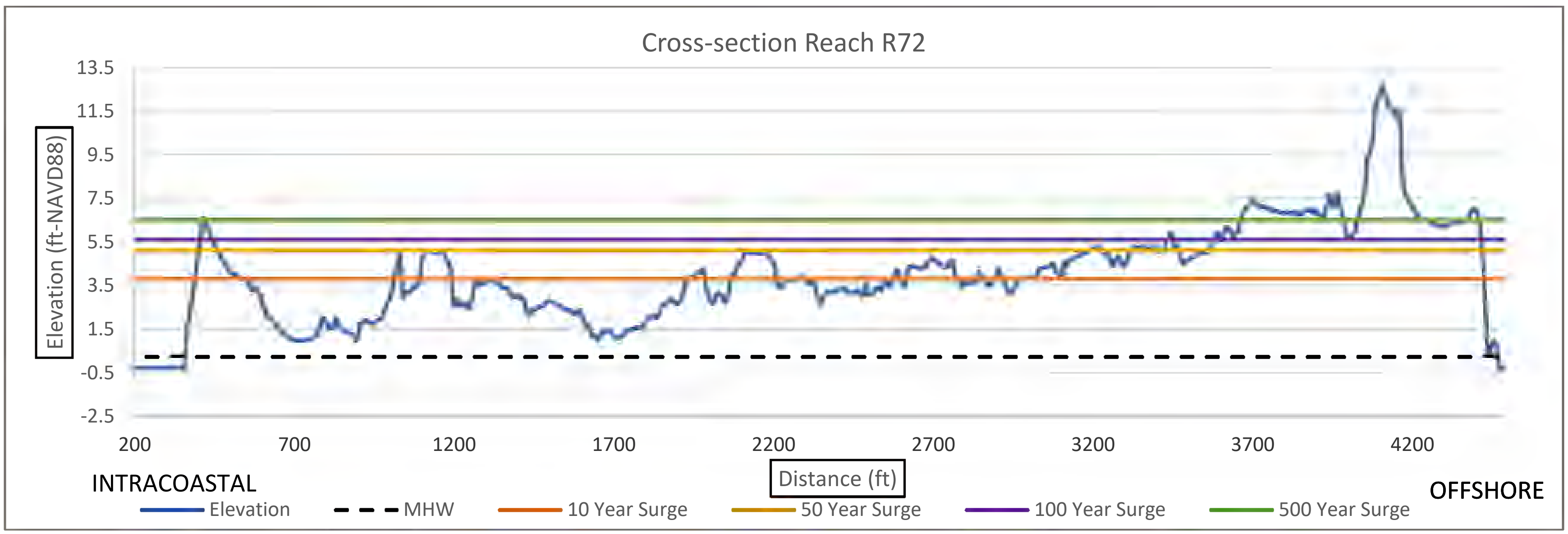
-2.5
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R71.5
Elevation (ft-NAVD88)
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
400
900
1400
1900
2400
2900
3400
3900
4400
4900
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R72
Elevation (ft-NAVD88)
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9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
200
700
1200
1700
2200
2700
3200
3700
4200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
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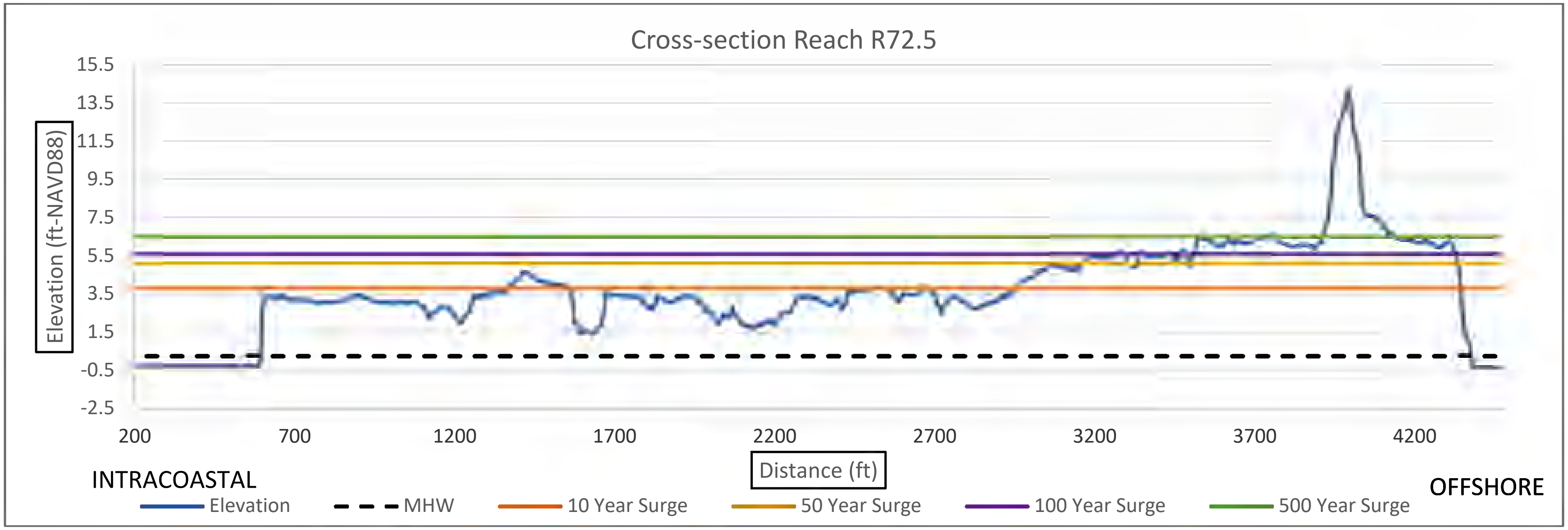
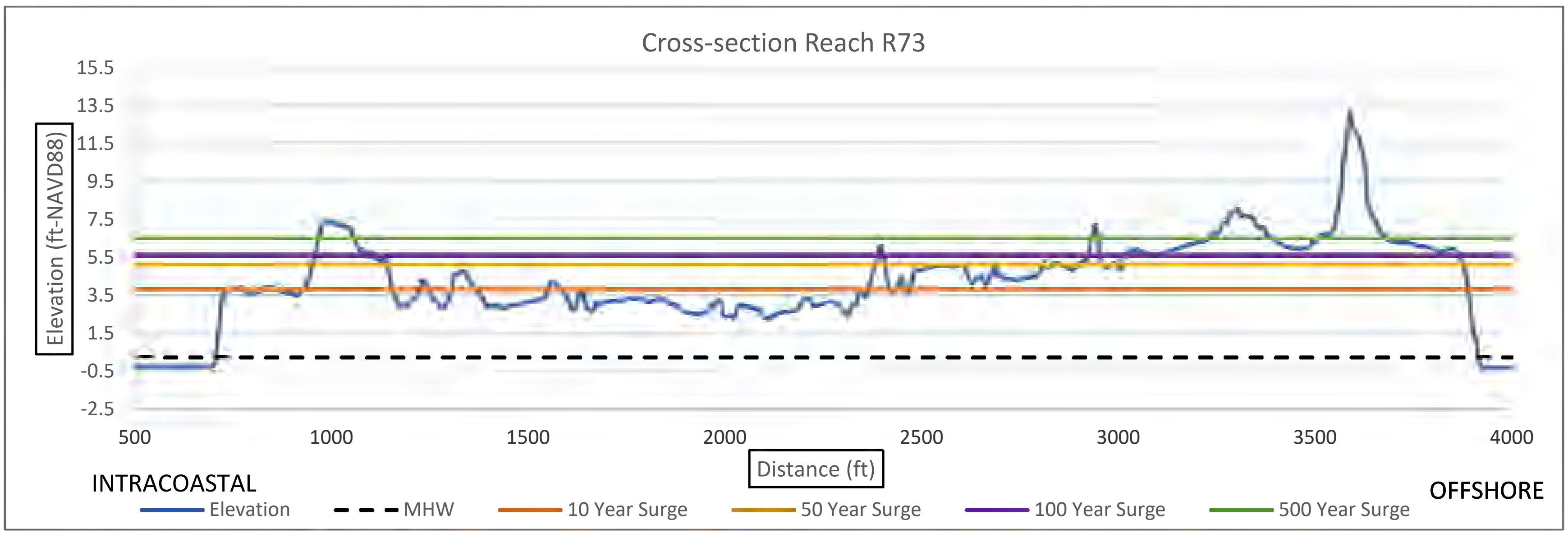
100 Year Surge
500 Year Surge


Cross-section Reach R72.5
Elevation (ft-NAVD88)
15.5
13.5
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
200
700
1200
1700
2200
2700
3200
3700
4200
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R73
Elevation (ft-NAVD88)
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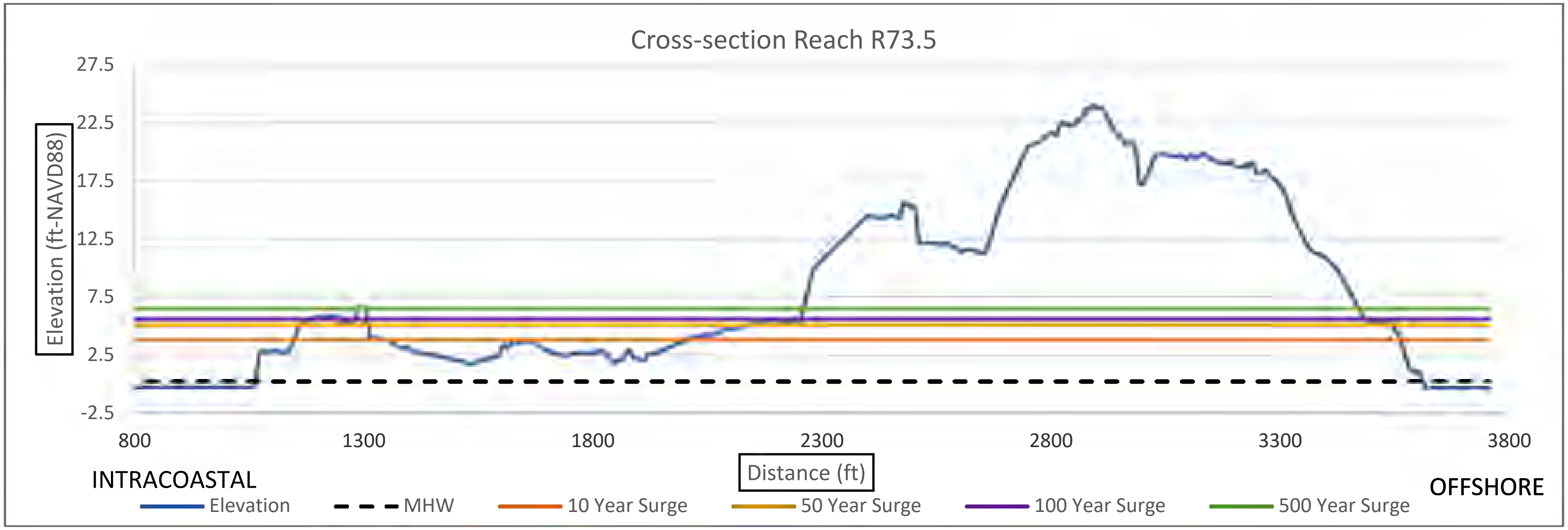
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
500
1000
1500
2000
2500
3000
3500
4000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R73.5
Elevation (ft-NAVD88)
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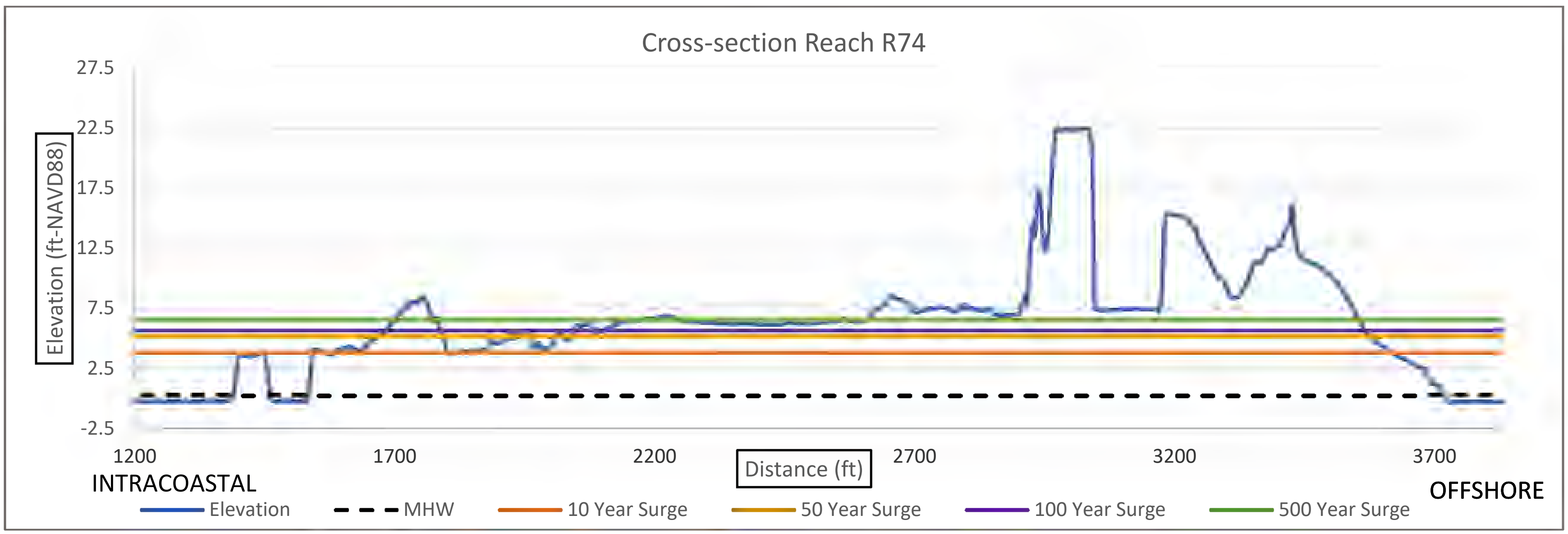
22.5
17.5
12.5
7.5
2.5
-2.5
800
1300
1800
2300
2800
3300
3800
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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Elevation (ft-NAVD88)
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17.5
12.5
7.5
2.5
-2.5
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1700
2200
2700
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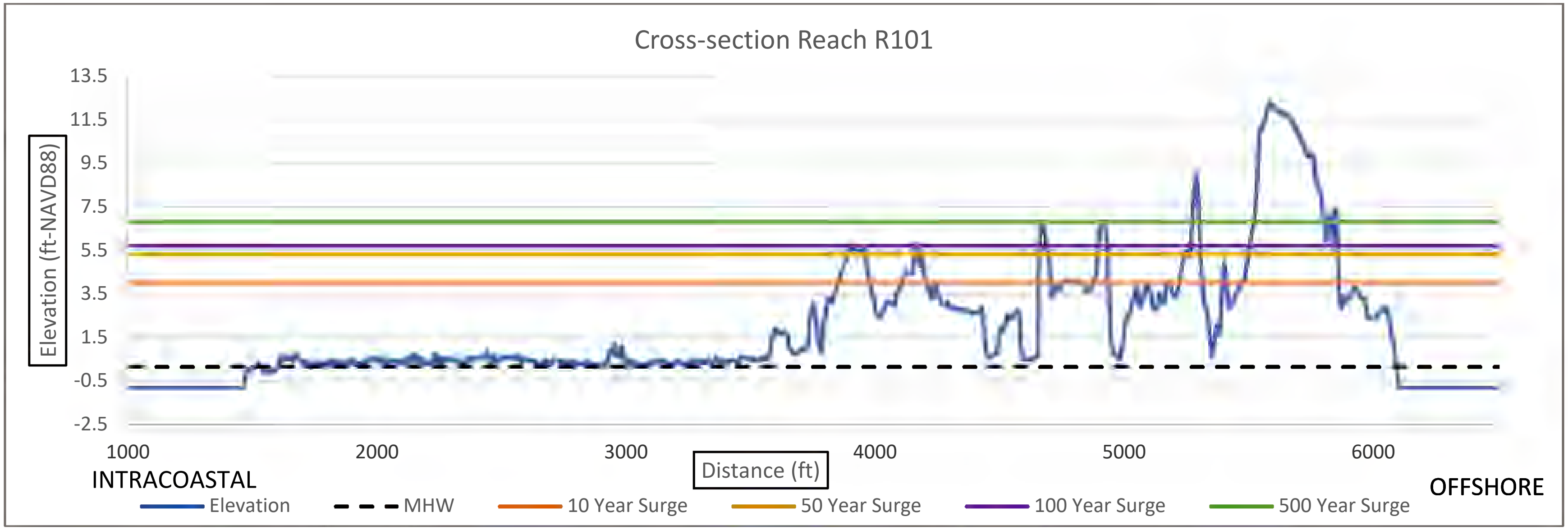
3700
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge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1000
2000
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Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
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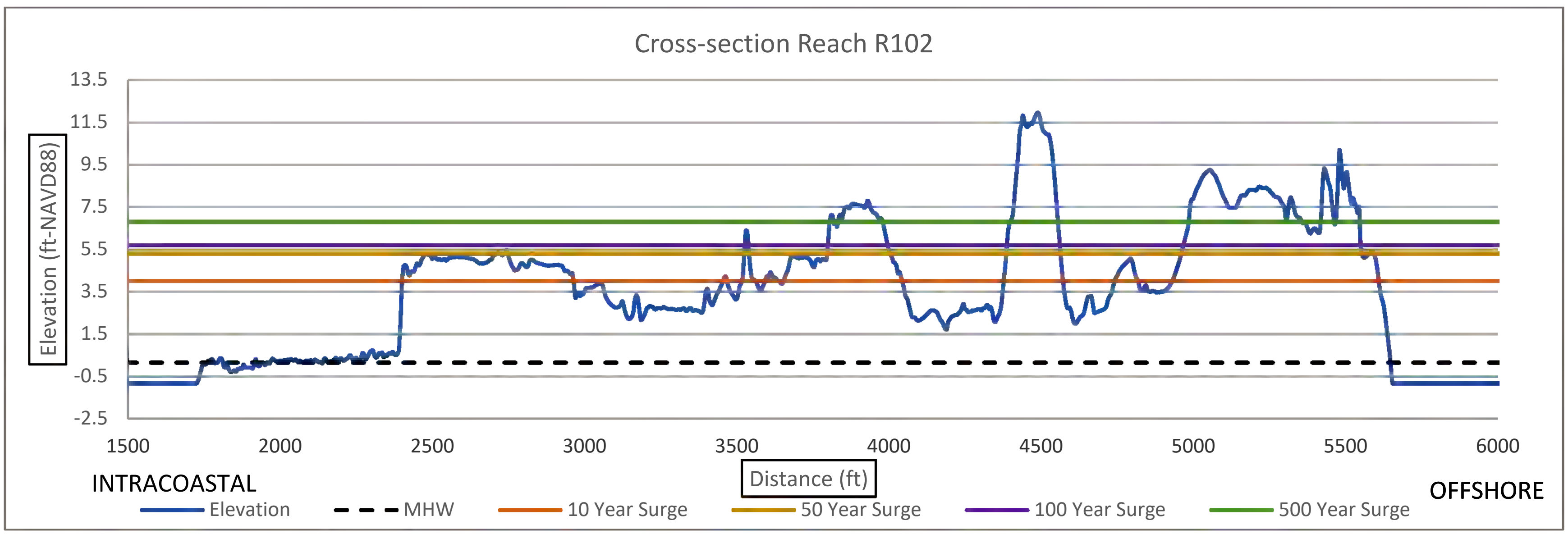
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Elevation (ft-NAVD88)
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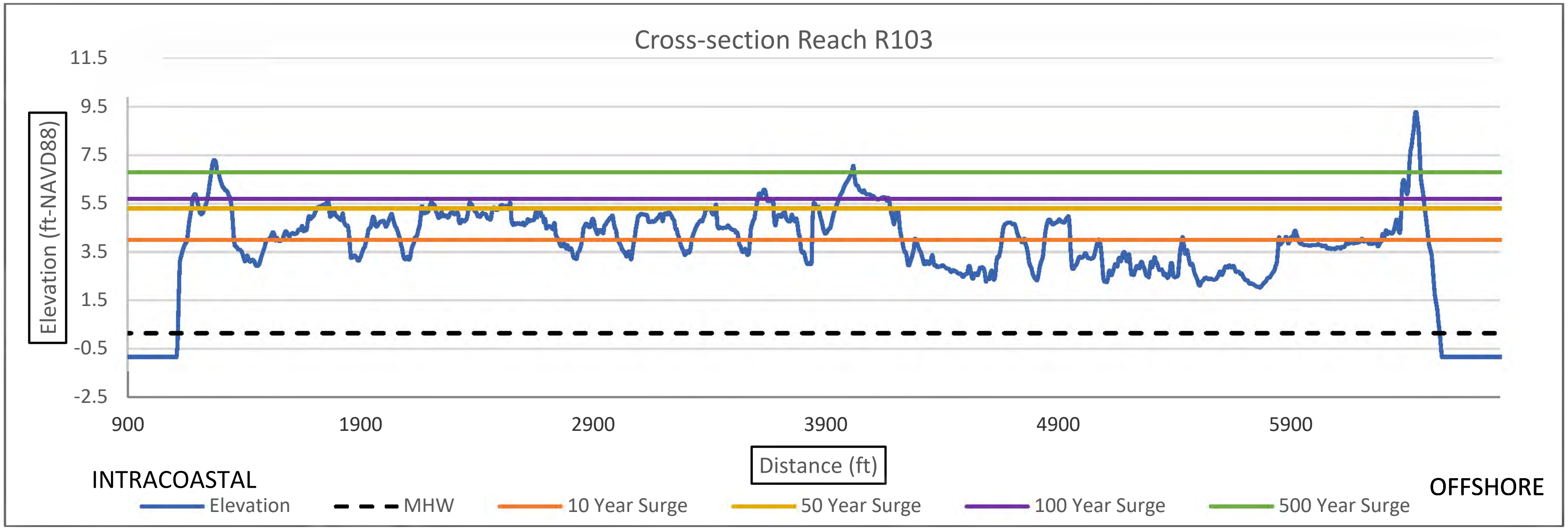
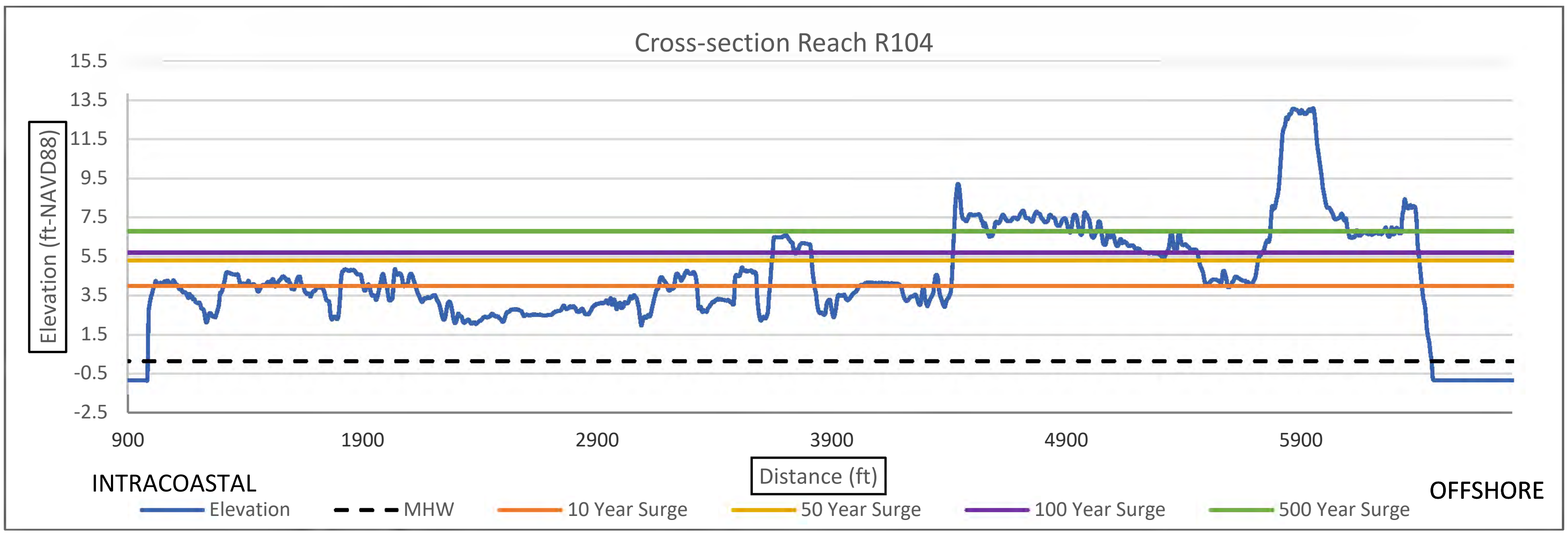
-2.5
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R103
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
900
1900
2900
3900
4900
5900
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge



Cross-section Reach R104
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11.5
9.5
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5.5
3.5
1.5
-0.5
-2.5
Elevation (ft-NAVD88)
900
1900
2900
3900
4900
5900
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
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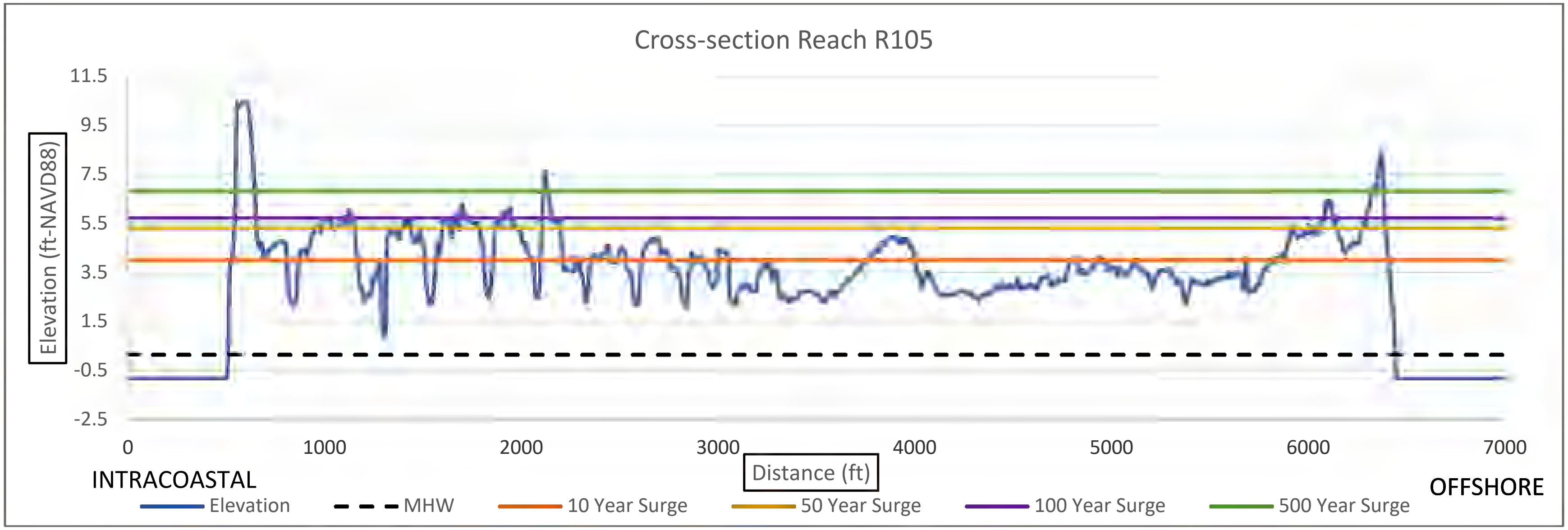
100 Year Surge
500 Year Surge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Elevation (ft-NAVD88)
11.5
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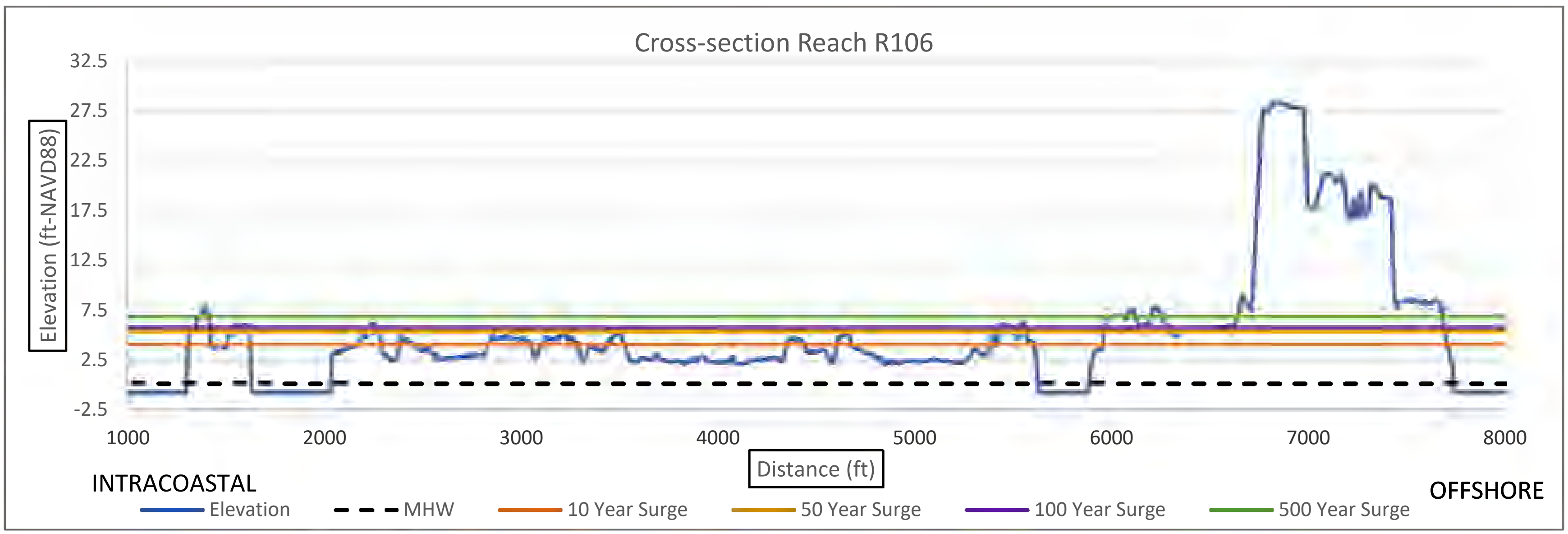
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R106
Elevation (ft-NAVD88)
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7.5
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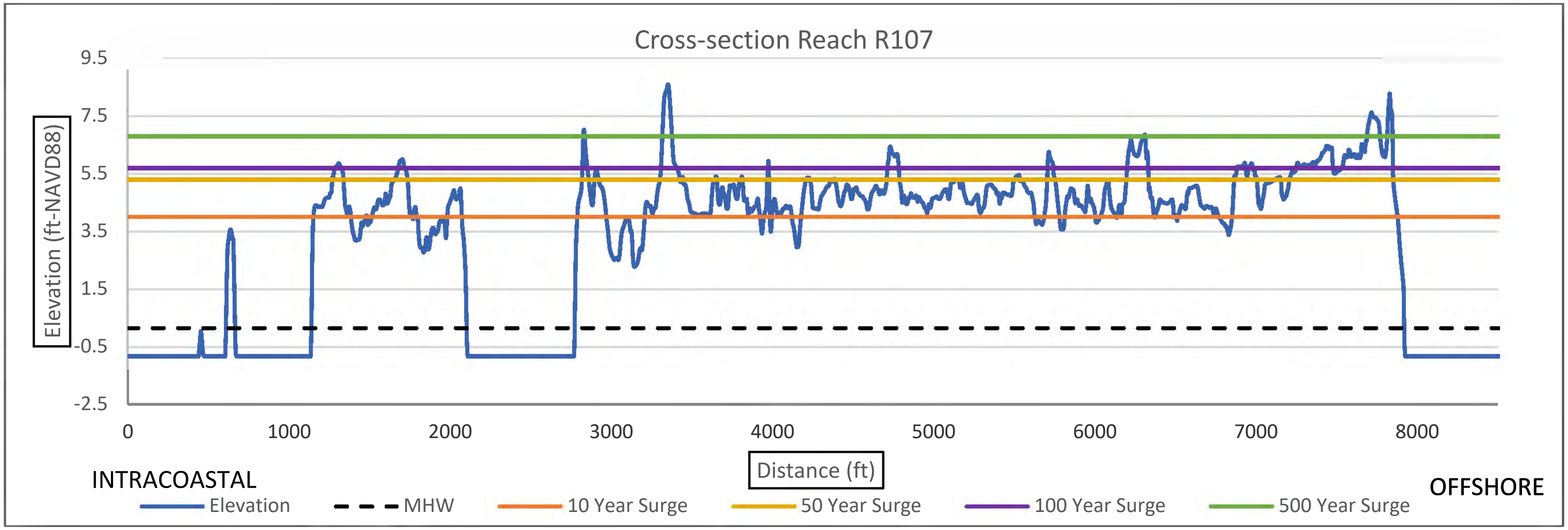
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge


Cross-section Reach R107
Elevation (ft-NAVD88)
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
7000
8000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
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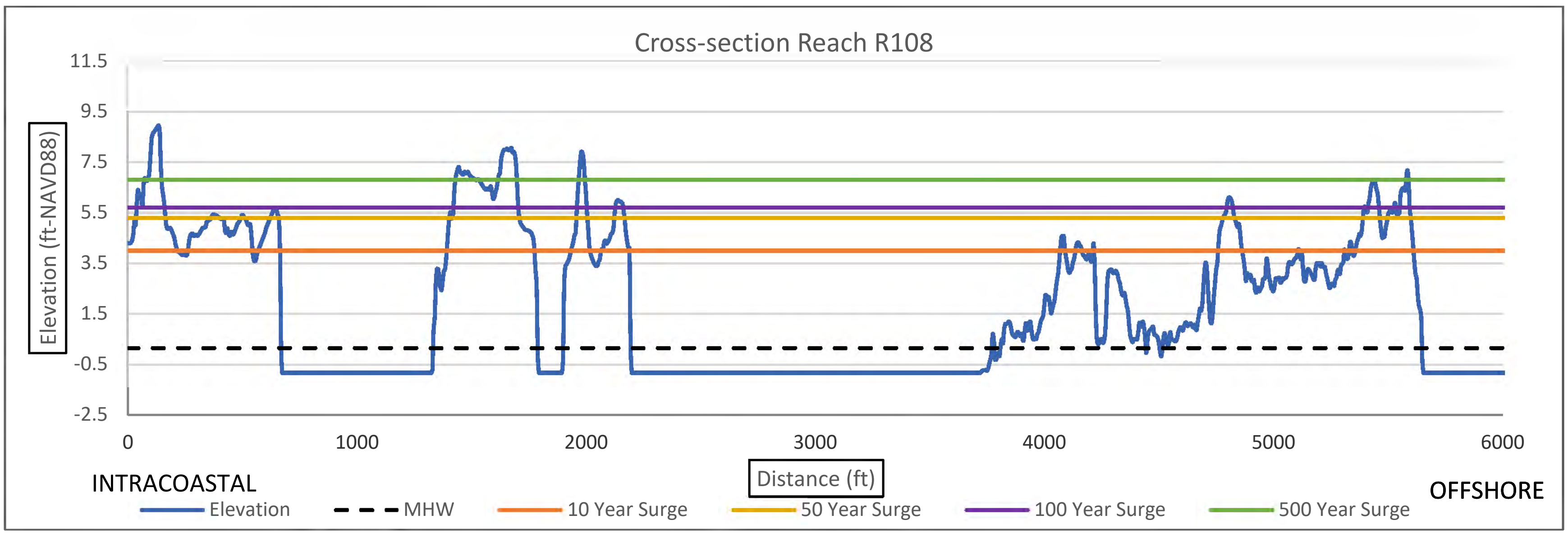
100 Year Surge
500 Year Surge


Cross-section Reach R108
Elevation (ft-NAVD88)
11.5
9.5
7.5
5.5
3.5
1.5
-0.5
-2.5
0
1000
2000
3000
4000
5000
6000
Distance (ft)
INTRACOASTAL
OFFSHORE
Elevation
MHW
10 Year Surge
50 Year Surge
100 Year Surge
500 Year Surge

MIAMI-DADE COUNTY, FLORIDA
COASTAL STORM RISK MANAGEMENT

Engineering Sub-Appendix A-1

Determination of Background Shoreline Change

Miami-Dade County, FL

November 2021

U.S. ARMY CORPS OF ENGINEERS
JACKSONVILLE DISTRICT

US Army Corps
of Engineers ®
Jacksonville District

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Determination of Background Shoreline Change

Miami-Dade County, FL

Beach-*fx* requires the use of shoreline change rates to represent the planform diffusion of the beach fill alternatives after placement. Traditionally the one-dimensional shoreline change model GENESIS (Hanson and Kraus 1989), a PC-based program capable of simulating long-term spatial changes in longshore transport, has been employed for USACE feasibility studies. However, model setup, calibration, verification, and application to an array of beach renourishment alternatives can be complex and time consuming.

Traditional schedules are accelerated under SMART planning guidelines, so an alternative methodology to determine shoreline change rates is used in this feasibility study. For the Miami-Dade Coastal Storm Risk Management Study, the shoreline change rates are determined using historical survey data in the project area.

Available beach surveys for Miami-Dade County go back as far as 1851, but the reliability of such historical data may be questionable. Actual dates oftentimes span multiple years, and survey line locations may not be consistent with current survey data. Additionally, conditions within the project area have changed over time due to development, an existing beach nourishment program, changing environmental conditions, and coastal structures among other things.

The 2016 Dade County, Florida BEC&HP Project Limited Reevaluation Report (LRR) (USACE, 2016) utilized surveys from 2005 to 2014 in the volume change analyses. As noted in the LRR, it is normally desirable to use surveys spanning the longest period available to establish more reliable long-term shoreline change rates and smooth year-to-year noise. However, constraints limit the availability and applicability of certain sets of survey data within Miami-Dade County. As discussed below, these factors can be the survey control, beach nourishment events, construction of coastal structures, and the impact of uncharacteristically severe storms.

1 MIAMI-DADE COUNTY MAIN SEGMENT

1.1 SHORELINE CHANGE

In the Miami-Dade County Main Segment, the initial monitoring of the project was along USACE-established monitoring lines. These lines were transitioned to FDEP R-Monument lines in the early 1990s. Comparison between surveys prior to this transition were at different locations and along different azimuths than current day surveys. Any comparison would require interpolation of an older survey data set onto the current day profile lines, which can introduce errors into the dataset. This limits the period of analysis to the late 1990s to the present.

In response to accelerated erosion observed along several reaches of the Main Segment, protective structures were constructed to reduce sediment losses at 32nd St in Miami Beach (R-60) and at the south end of the project at Government Cut. These improvements were made in the late 1990s and early 2000s. These structures strongly altered the patterns of sediment movement in these regions, and for the purposes of determining present day sedimentation patterns, construction of these structures rendered the older, pre-construction surveys obsolete.

Additionally, an ongoing beach nourishment program has been happening since the early 1970s (Miami-Dade BEC&HP Project) which has featured numerous beach fills within the Main Segment. Between local and Federal efforts, over 15 beach placements have taken place since 2000, including a backpassing event in 2011 where sand was removed from one portion of the beach and placed on another. With such an extensive placement history, any survey chosen for analysis will feature some influence from beach nourishment; however, that can be minimized through careful consideration of the timing and spatial influence of the events.

Notable periods of unusually severe storm activity have impacted the project. In 2004 and 2005 an unusual combination of hurricanes and tropical storms impacted the region which resulted in large volumes of sediment being driven out into deeper water and then a slow recovery of the nearshore system. Similarly, in 2016 and 2017 the project area was impacted by hurricanes, again resulting in large amounts of cross-shore transport and the process of post-storm recovery. While storms are part of the natural coastal processes and are typically included in shoreline change analyses, extreme storms that occur during periods with short survey intervals can skew the measured shoreline change rate. As a result, if a large storm cannot be included within a longer survey period, the surveys that include the storm may need to be screened out of the analysis if it is determined that they would overrepresent the erosion in the project area.

The period used to establish an annual shoreline change rate must be representative of present-day conditions along the Miami-Dade County shoreline. It should also try to exclude the effects of unusually severe and infrequent storms within short survey intervals that could overrepresent erosion and the influence of construction projects (beach and structural) whenever possible. Ideally the surveys used will span a multi-year timeframe to eliminate the year-to-year variability of the beach profile. The survey data must be compatible (in terms of location) with current day surveys. Based on these factors, the analysis for the Main Segment of Miami-Dade County is limited to available surveys between 2005 and the present.

The surveys taken in 2005 feature the impacts and response from the 2004 hurricanes but occur in the middle of a multi-year lull in construction activity. The surveys taken in 2007 feature the impacts from nourishment along the Bal Harbour, 44th Street (R-56), and 27th Street (R-61) hotspots. Likewise, the 2009 surveys feature the impacts of local nourishments in Bal Harbour and the northern and middle portions of Miami Beach (65th Street (R-45), 55th Street (R-50) and 44th Street hotspots). The 2011 survey occurred in a period relatively devoid of manmade influences outside of a small maintenance disposal at Bal Harbour. The 2014 survey was the basis for analysis in the 2016 LRR and occurred after the 2011 Contract E beach renourishment which featured backpassing from R-64 to R-69 and placement near the 27th Street, 44th Street, and 65th Street hotspots. This survey did occur just prior to Federal and local nourishments in Bal Harbour and Surfside in 2014. In 2016 two lidar surveys were taken before and after Hurricane Matthew. In between these surveys, a hotspot renourishment was partially constructed at the 44th Street hotspot. In 2017 a lidar survey was flown after Hurricane Irma which incorporates the direct impacts of the storm and the completed hotspot nourishment at the 44th Street and 55th Street hotspots. The 2018 survey falls after the 2016 and 2017 hurricanes and the 2016 to 2017 hotspots nourishment project. The final available survey is a county-wide survey completed by Miami-Dade County in 2019.

For all surveys discussed above, the distance from each FDEP R-monument to the mean high water (MHW) line is in Table 1. Figure 1 shows the MHW position at each R-monument relative to the 2005 MHW position for the surveys between 2005 and 2019. The frequent nourishment events and hotspot areas are evident in the figure (near R-47 and R-55). Also in the figure, the effects of utilizing a beach borrow area (near R-65) in the 2011 nourishment are shown.

Table 1. Main Segment Distance (ft) from FDEP R-Monument to the MHW Line 2005 to 2019

R-Mon	Distance to MHW from the R-Mon (ft)									
	Feb 2005	Aug 2007	Dec 2009	April 2011	Jan 2014	July 2016 (Pre-Matthew)	Dec 2016 (Post-Matthew)	Oct 2017	Sep 2018	Oct 2019
27	376.3	341.3	302.5	326.5	311.8	371.3	338.2	351.7	370.2	287.0
28	307.4	265.5	268.2	273.7	243.0	307.5	262.7	277.4	261.6	274.6
29	296.6	281.1	265.3	285.2	236.0	291.4	302.9	236.3	252.4	235.5
30	167.4	165.9	162.5	165.5	123.9	200.2	190.8	149.4	165.8	159.8
31	165.7	145.0	117.4	136.0	103.5	171.6	152.2	139.5	124.0	126.6
32	360.8	321.7	303.6	329.0	303.0	342.5	336.8	319.7	290.1	289.8
33	377.1	362.5	364.0	333.3	332.6	351.7	319.3	332.6	340.4	322.1
34	400.7	393.4	366.7	367.0	353.8	341.6	377.5	361.3	357.3	340.9
35	370.1	364.0	369.8	382.1	346.9	343.0	325.7	327.1	317.9	329.5
36	328.0	304.9	283.3	284.4	304.5	311.0	287.1	276.9	255.7	368.9
37	313.1	296.1	270.8	270.0	266.0	290.0	280.4	267.8	260.0	259.1
38	305.6	271.3	277.1	264.2	286.1	268.6	275.3	276.2	313.5	307.5
39	334.9	346.6	353.8	340.4	309.4	342.0	332.4	335.3	335.4	354.9
40	408.8	377.8	383.6	386.4	369.3	407.4	410.2	408.9	398.0	409.6
41	186.3	197.8	177.2	182.6	196.2	203.8	200.3	188.7	203.5	167.1
42	204.4	263.5	207.7	204.1	251.8	223.2	231.4	229.8	219.9	207.5
43	177.6	151.3	140.4	161.4	190.3	207.4	176.8	188.5	156.4	176.0
44	138.1	103.3	176.4	145.8	211.1	148.8	175.5	152.5	138.8	144.0
45	335.4	312.5	279.2	264.8	358.3	310.7	354.9	314.3	322.2	312.7
46	137.4	148.1	110.3	117.9	169.8	155.8	121.4	120.3	122.8	130.2
47	500.8	525.1	502.5	474.3	509.1	486.7	539.0	510.0	518.0	495.6
48	288.1	282.7	272.5	301.7	286.9	323.8	281.6	313.6	306.3	301.4
49	207.3	194.5	220.9	199.1	201.8	191.4	197.3	239.6	232.5	216.6
50	62.4	77.5	72.1	50.6	27.0	30.0	22.7	71.2	56.1	53.9
51	392.7	350.1	358.0	400.8	338.6	377.2	368.6	396.0	398.4	377.2
52	280.6	283.8	291.3	283.2	248.7	245.8	240.1	280.5	256.9	258.7
53	204.2	157.3	204.4	186.4	181.1	198.9	202.8	191.4	219.4	218.7
54	485.6	458.0	466.5	447.0	465.8	466.3	556.0	500.9	489.5	476.4
55	107.3	111.6	82.5	101.3	130.1	115.0	110.0	155.4	144.6	138.0
56	126.6	136.9	129.6	146.2	153.6	154.3	210.2	197.8	181.2	186.4
57	305.6	276.0	336.1	317.3	290.5	389.2	339.3	381.6	398.9	385.4
58	332.8	401.4	396.3	406.1	435.5	448.8	438.0	426.1	434.1	436.4
59	528.1	530.3	528.7	529.5	527.6	528.8	540.2	530.3	523.1	522.7
60	421.5	419.7	426.0	426.8	423.0	423.8	431.3	425.5	410.0	428.3
61	144.6	124.2	165.0	168.4	164.2	132.3	143.1	184.6	186.4	150.6
62	230.8	176.9	207.5	212.5	199.3	191.3	174.3	200.8	209.7	202.1
63	550.0	517.3	495.2	511.0	498.0	484.2	504.3	485.9	480.4	488.7
64	519.6	511.2	525.1	514.7	485.5	483.6	494.6	467.2	487.3	452.6
65	752.1	755.0	777.9	782.0	758.0	759.9	738.7	734.3	701.8	750.1
66	459.5	471.7	503.7	514.0	488.3	502.4	492.0	490.5	488.1	479.5
67	567.9	559.5	626.4	634.5	625.5	619.7	620.4	610.6	614.1	610.1
68	543.4	589.6	596.6	623.9	624.3	619.6	624.5	625.9	624.2	626.8
69	548.3	598.4	574.5	611.5	613.4	633.6	655.1	644.0	626.7	632.4
70	651.7	696.6	690.9	727.6	717.1	753.2	733.8	741.5	767.1	717.9
71	305.3	334.0	334.3	341.1	345.5	362.4	368.0	371.6	371.1	374.6
72	307.3	334.3	344.5	354.2	370.4	400.2	398.4	403.7	396.3	388.3
73	231.7	218.6	247.3	240.6	287.0	299.0	317.3	295.6	319.8	316.1
74	570.4	580.0	595.0	608.0	624.0	630.3	635.1	637.3	641.3	630.0

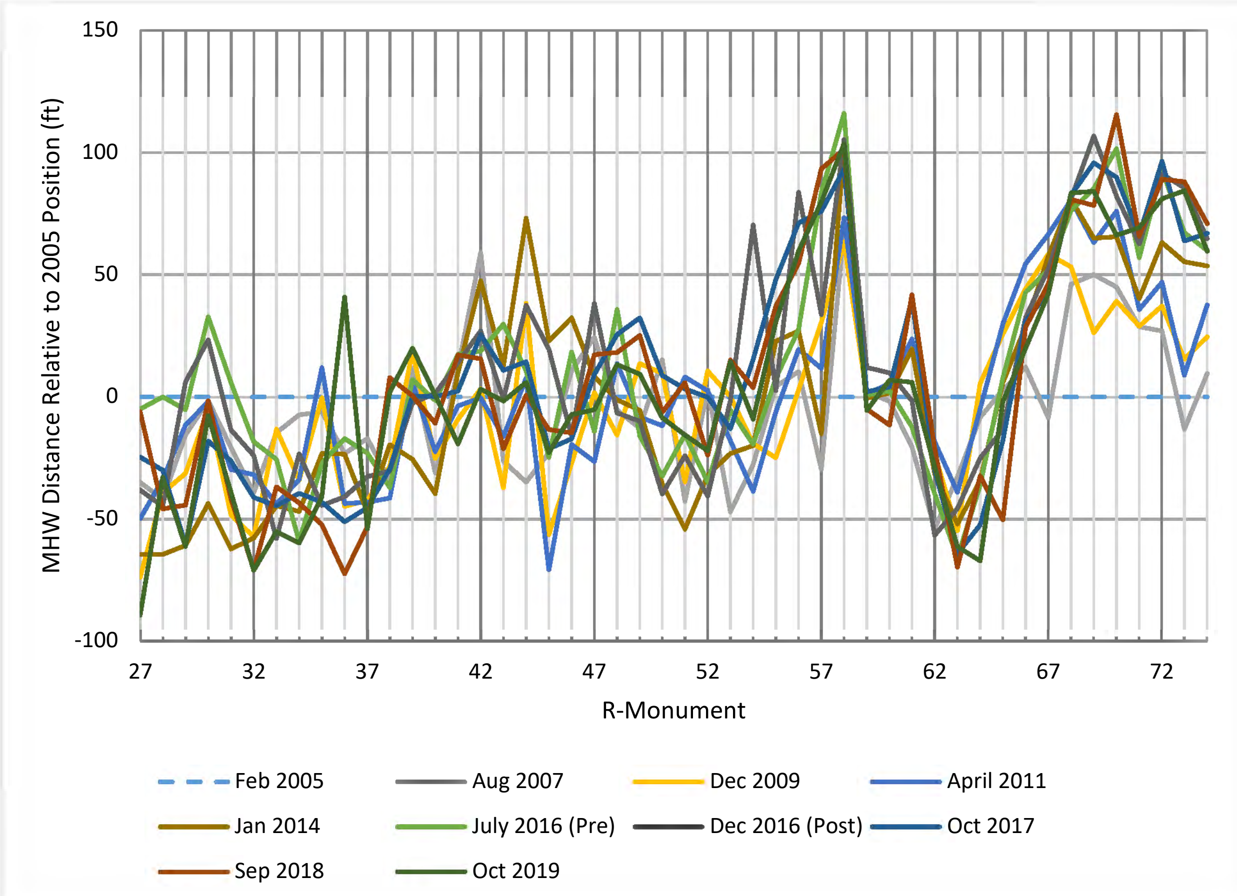

Figure 1. Main Segment MHW Position Relative to 2005 Position for Surveys between 2005 and 2019

1.2 BACKGROUND ANNUAL CHANGE RATES

The shoreline change rates between consecutive surveys were compared to get a sense of the short-term variation in Figure 2. The figure shows that the shoreline change rate when computed over short time intervals can vary significantly. Many hotspot nourishments can be seen in the plot represented by narrow positive spikes. The 2016 pre- to post-Hurricane Matthew period is not displayed because the annualized results are overemphasized due the large changes over a short period of time and are therefore not representative of expected annual rates.

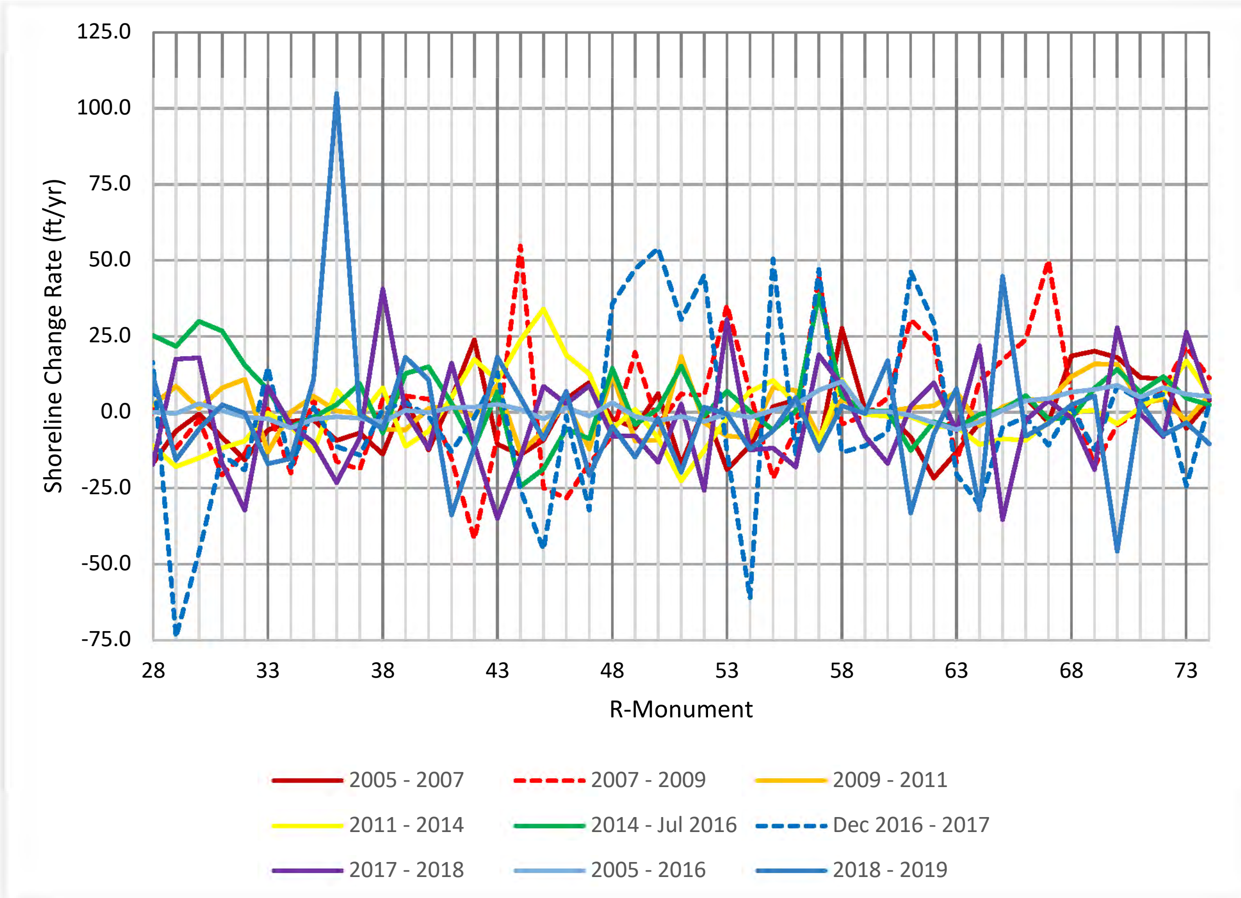

Figure 2. Shoreline Change Rate (ft/yr) between Consecutive Survey Events in the Main Segment of Miami-Dade County

For determination of a representative historical background shoreline change rate which will be used as a target shoreline change rate in the Beach-*fx* calibration, a longer period between surveys was examined as shown in Figure 3. As discussed above, there is no ideal period for comparison in the 2005 to present timeframe as nourishments have impacted the beach response.

The longest timeframe without beach nourishments was determined at each R-monument, and the shoreline change rate from this period was selected. From R-27 to R-31 the period was from 2011 to 2014. From R-32 to R-35, R-37 to R-39, R-57 to R-59, and R-63 to R-74 the longest time frame was from 2005 to 2019. From R-40 to R-47 and at R-60 the longest timeframe was 2016 to 2019. From R-48 to R-56 the longest timeframe was from 2017 to 2019 and from R-61 to R-62 the longest timeframe was from 2014 to 2016. R-36 used the period between 2005 and 2018 because the 2019 survey captured beach fill from the beginning of the 2019 Surfside renourishment project. This issue did not impact the other R-monuments in the project area.

Once this rate was determined on an R-monument-by-R-monument basis, the rates of three adjacent R-monuments (the monument in question, the one to the north, and the one to the south) were averaged together to smooth the shoreline change rates. This mimics the expected effects that would result from discontinuing the nourishment in these areas by increasing erosion in the adjacent areas. This averaging was not applied in areas with higher historical erosion rates because averaging the rates in those areas caused a significant underprediction of the historical rates. This selective averaging of the shoreline change rates yielded a representative background shoreline change pattern across the Miami-Dade Main Segment project area (Figure 3). The figure clearly shows the areas with higher historical erosion rates in Bal Harbour (R-28 to R-29), the hotspots at R-45 to R-46, R-49 to R-50, and R-54 to R-55, and the area south of the 32nd Street breakwaters at R-61, as well as more stable areas such as the Town of Surfside (R-35 to R-39) and Miami South Beach (R-67 to R-74). Table 2 shows the background shoreline change rate used in the Beach-*fx* modeling. The background erosion rate is higher in many areas than the long-term erosion rates. This demonstrates how the periodic beach nourishments over the life of the project have maintained a generally stable shoreline, counterbalancing the background shoreline change rate.

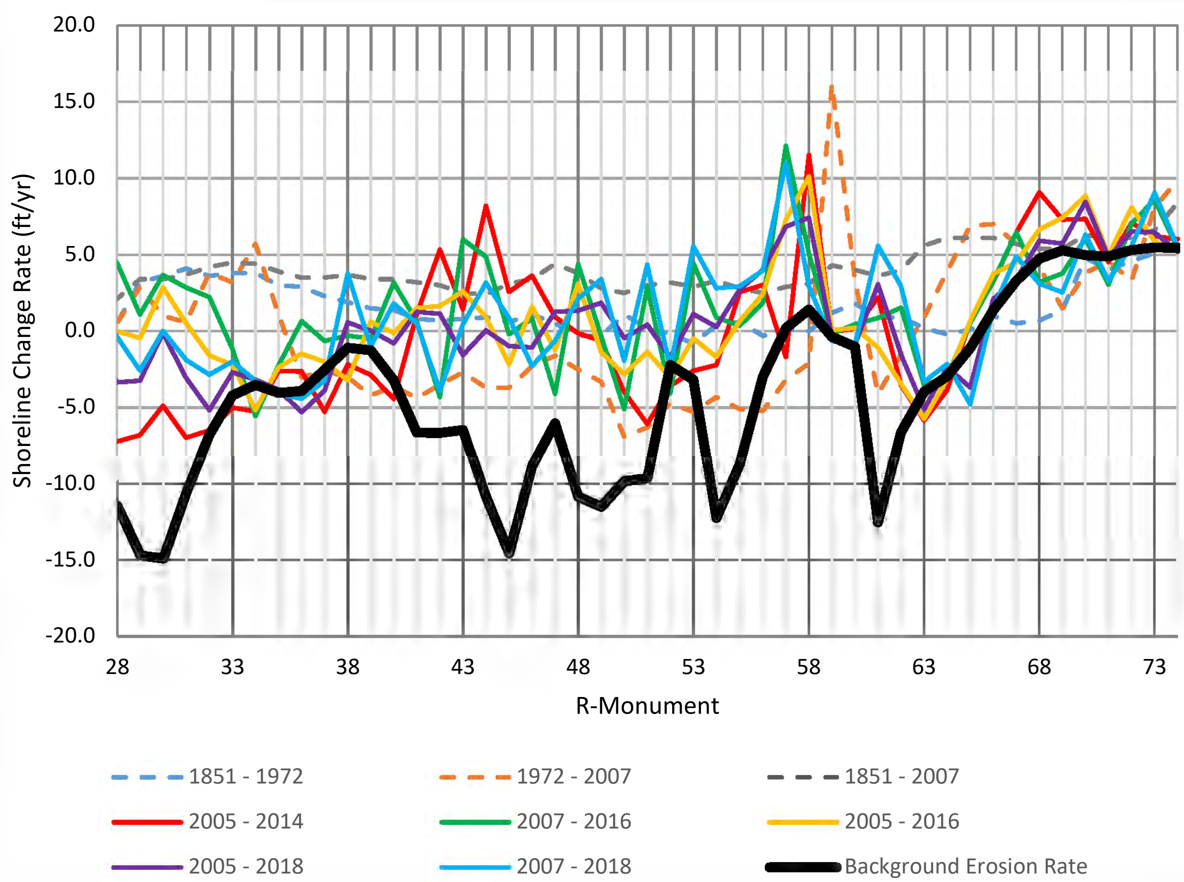

Figure 3. Shoreline Change Rate (ft/yr) between Longer Period Survey Events for the Main Segment of Miami-Dade County and the Background Shoreline Change Rate Used in the Beach-*fx* Modeling.

Table 2. Background Annual Shoreline Change Rate Used for Main Segment

FDEP R-Monument	Timeframe used During Analysis	Background Annual Shoreline Change Rate (ft/yr)
28	2011 - 2014	-11.45
29	2011 - 2014	-14.70
30	2011 - 2014	-14.91
31	2011 - 2014	-10.56
32	2005 - 2019	-6.78
33	2005 - 2019	-4.21
34	2005 - 2019	-3.52
35	2005 - 2019	-4.04
36	2005 - 2018	-3.90
37	2005 - 2019	-2.52
38	2005 - 2019	-1.08
39	2005 - 2019	-1.24
40	2016 - 2019	-3.22
41	2016 - 2019	-6.64
42	2016 - 2019	-6.66
43	2016 - 2019	-6.46
44	2016 - 2019	-10.86
45	2016 - 2019	-14.56
46	2016 - 2019	-8.83
47	2016 - 2019	-6.02
48	2017 - 2019	-10.87
49	2017 - 2019	-11.52
50	2017 - 2019	-9.85
51	2017 - 2019	-9.65
52	2017 - 2019	-2.22
53	2017 - 2019	-3.17
54	2017 - 2019	-12.25
55	2017 - 2019	-8.71
56	2017 - 2019	-2.99
57	2005 - 2019	0.20
58	2005 - 2019	1.41
59	2005 - 2019	-0.37
60	2016 - 2019	-1.03
61	2014 - 2016	-12.51
62	2014 - 2016	-6.61
63	2005 - 2019	-3.96
64	2005 - 2019	-2.95
65	2005 - 2019	-1.11
66	2005 - 2019	1.36
67	2005 - 2019	3.29
68	2005 - 2019	4.74
69	2005 - 2019	5.29
70	2005 - 2019	4.97
71	2005 - 2019	4.90
72	2005 - 2019	5.31
73	2005 - 2019	5.47
74	2005 - 2019	5.46

2 MIAMI-DADE COUNTY KEY BISCAYNE SEGMENT

2.1 SHORELINE CHANGE

The earliest available surveys in Key Biscayne are from 1913, 1919, and 1927. However, surveys in this area are scattered and do not cover the entire project area from R-101 to R-108. The period from 1927 to 1980 contained multiple surveys that covered the entire project area and represented the time prior to any beach nourishment projects in the area. The first beach nourishment in the project area occurred in 1987, and surveys of the shoreline become more frequent starting in 1996. Profiles prior to 1996 were reviewed for information but excluded from this analysis because of the unreliability and infrequency of older surveys.

It is important for the surveys used in the analysis to disregard the influence of beach fills and represent the present-day background shoreline change rates of the project area. Nourishment events have occurred five times in the project area (1987, 2002, 2008, 2012, and 2017), and the surveys taken directly after these events have been excluded from the analysis to reduce the influence of the beach nourishments on the dataset. Additionally, any periods with extreme changes to the shoreline are also excluded because the time between surveys is relatively short, and the large shoreline changes within this period are not representative of the long-term rate. Table 3 shows the distance from the R-monuments to the MHW line for the period from 1996 to 2019. The highlighted columns represent surveys that were used during the analysis. Figure 4 shows the MHW position of all the available surveys relative to the 1996 MHW position.

Table 3. Key Biscayne Distance (ft) from FDEP R-Monument to MHW Line 1996 to 2019

R-Mon	Jun 1996	Sep 1997	Jul 1998	Jan 2003	Sep 2003	Feb 2005	Dec 2005	Aug 2007	Dec 2009	Feb 2011	Aug 2011	May 2012	Jul 2012	Sep 2013	Jul 2014	July 2015	May 2016	Nov 2018	Oct 2019
R-101	189	202	214	258	267	274	271	273	323	339	354	366	370	360	384	383	383	364	342
R-102	188	180	195	211	247	280	250	249	247	256	257	241	266	274	290	292	299	315	301
R-103	53	39	39	72	77	58	53	49	53	49	47	27	65	63	73	74	75	120	
R-104	90	80	83	94	101	75	82	64	49	44	58	38	74	71	67	59	46	62	57
R-105	93	83	86	120	112	106	99	103	94	88	87	74	100	98	102	99	92	94	87
R-106	72	71	70	111	82	89	87	80	71	63	58	58	85	67	72	71	67	67	66
R-107	208	203	200	229	221	219	227	216	204	200	194	197	219	202	208	203	202	209	204
R-108	182	183	189	175	184	175	182	191	190	193	198	188	194	191		194	189	194	173

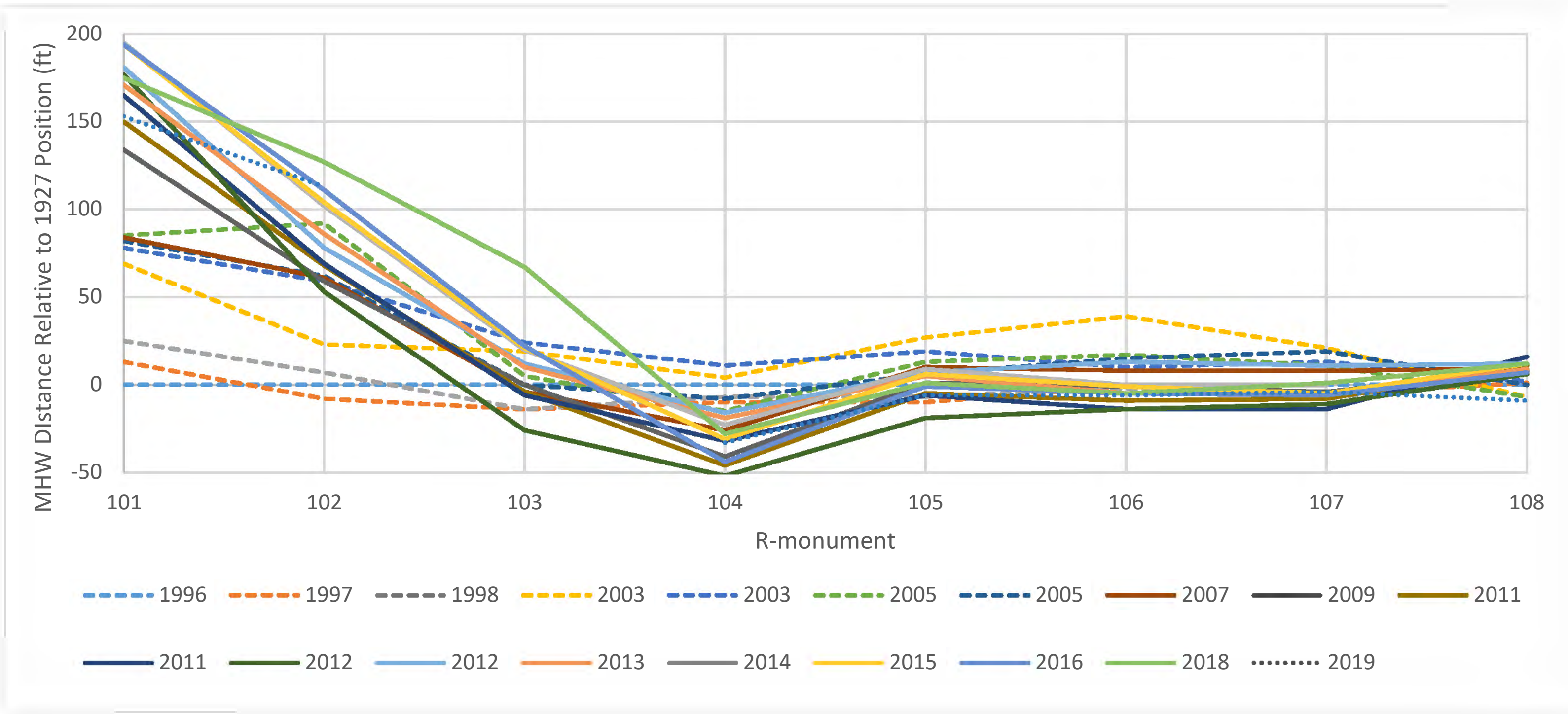

Figure 4. Key Biscayne Distance (ft) Relative to 1996 MHW Position for Surveys between 1996 and 2019

2.2 BACKGROUND ANNUAL CHANGE RATES

For an evaluation of the shoreline change rate, surveys were compared in

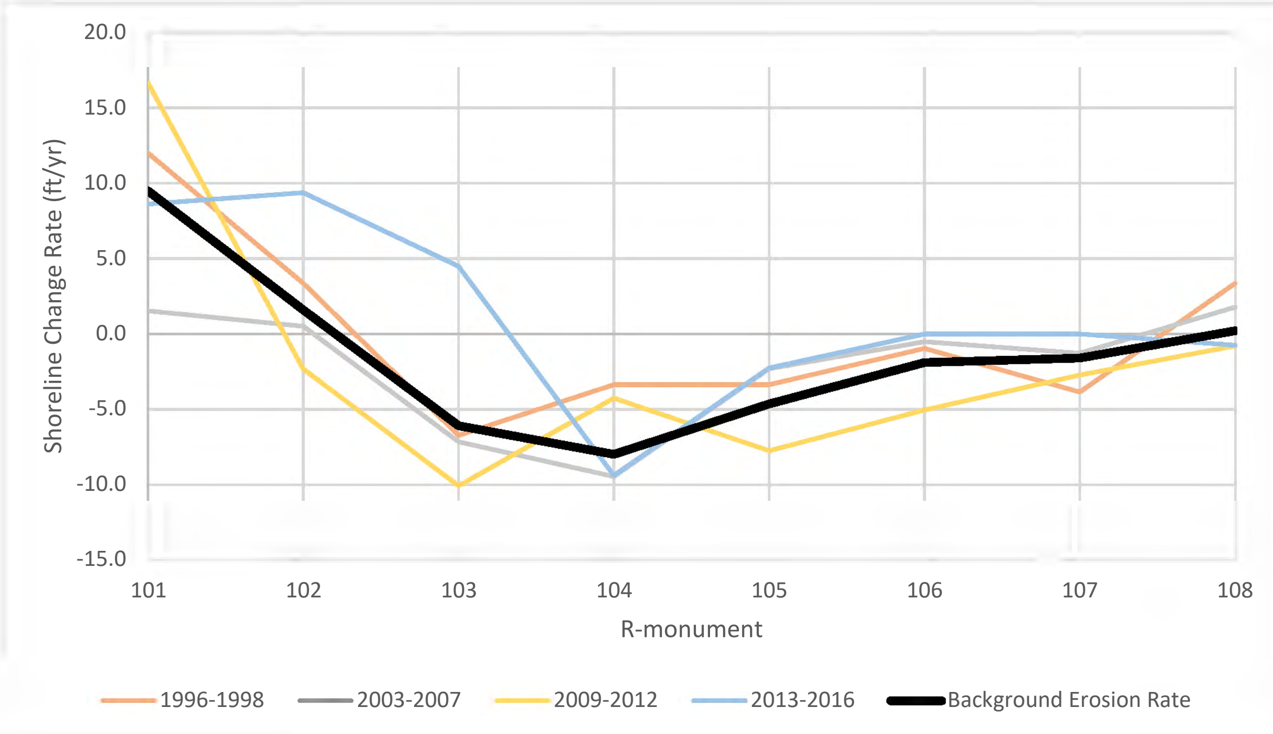

Figure 5 to get a sense of the variation of the shoreline. The time intervals depicted within the figure are averaged together (excluding survey years that were influenced by a beach nourishment) using a weighted average based on the length of time between surveys to determine the background shoreline change rate at each R-monument (Table 4). The time periods used during this analysis were from June 1996 to July 1998, September 2003 to August 2007, December 2009 to May 2012, to August 2007, and September 2013 to May 2016. The time periods between 1998 to January 2003, January 2003 to September 2003, 2007 to 2009, 2012 to 2013, 2016 to 2018, and 2018 to 2019 were excluded from this analysis because they either include a beach nourishment project during these time periods or show heavy influence from a beach nourishment.

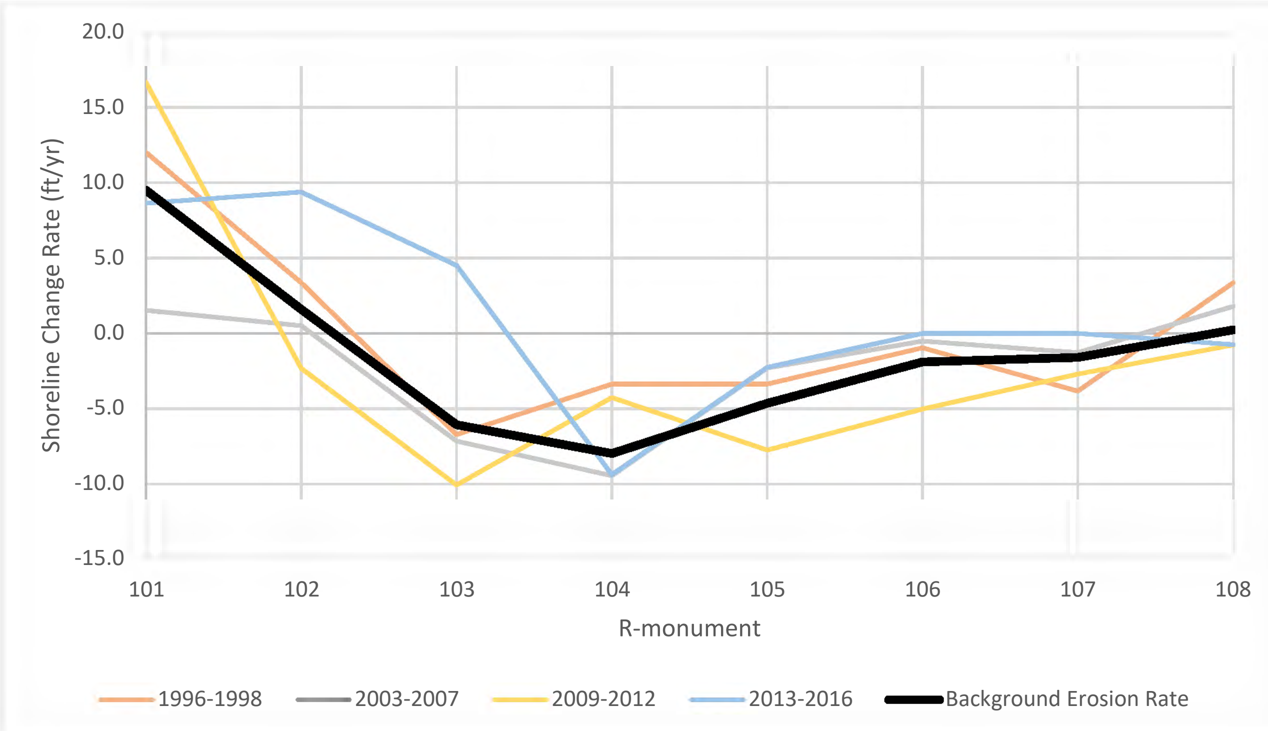

Figure 5. Shoreline Change Rate (ft/yr) between Survey Events in the Key Biscayne Segment of Miami-Dade County

Table 4. Background Annual Shoreline Change Rate at Key Biscayne R-Monuments

R-Monument	Background Shoreline Change Rate (ft/yr)
R-101	9.49
R-102	1.59
R-103	-6.08
R-104	-7.97
R-105	-4.63
R-106	-1.90
R-107	-1.59
R-108	0.23

The Main Segment Beach-*fx* model is divided into model reaches which are approximately 1,000 feet long centered on one R-monument per model reach. For the Key Biscayne Segment, the Beach-*fx* model reaches are 1,200 to 2,000 feet long and include multiple R-monuments. To determine a representative background shoreline change rate for each reach, multiple R-monuments representing the model reach were averaged together to determine the shoreline change rate used for modeling. The background shoreline change rates used for the Beach-*fx* modeling are shown in Table 5.

Table 5. Background Annual Shoreline Change Rate for Key Biscayne Model Reaches

Model Reach Name	Model Reach Boundaries	R-Monuments Included in Average for Background Annual Shoreline Change Rate	Background Annual Shoreline Change Rate (ft/yr)
R102	R-101.3 to R-103	R-102 & R-103	-2.24
R104	R-103 to R-105	R-103, R-104, & R-105	-6.23
R106	R-105 to R-106.6	R-105 & R-106	-2.71
R107	R-106.6 to R-107.9	R-107 & R-108	-0.68

3 REFERENCES

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