# PUERTO RICO COASTAL

## DRAFT INTEGRATED FEASIBILITY REPORT AND ENVIRONMENTAL ASSESSMENT

## APPENDIX A
## Engineering

June 2023

US Army Corps of Engineers ®
Jacksonville District

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## List of Acronyms

| | |
|---|---|
| 1D | one dimensional |
| 2D | two dimensional |
| 3D | three dimensional |
| ADCIRC | Advanced Circulation |
| AEP | annual exceedance probability |
| AER | applied erosion rate |
| BBA | Bipartisan Budget Act |
| BCR | benefit to cost ratio |
| BER | background erosion rate |
| CARICOOS | Caribbean Integrated Coastal Ocean Observing System |
| CCCL | Coastal Construction Control Line |
| CHS | Coastal Hazards System |
| CMP | Caño Martín Peña |
| CO | Condado (station number/model reach designation) |
| CSRM | Coastal Storm Risk Management |
| cy | cubic yards |
| DE | Damage Element |
| DEM | Digital Elevation Model |
| DoE | design of experiments |
| EAP | Emergency Action Plan |
| ECB | Engineering Construction Bulletin |
| ECL | Erosion Control Line |
| EDB | emergency deployable barriers |
| EM | Engineering Manual |
| EP | Engineering Pamphlet |
| ER | Engineering Regulation |
| ERDC | Engineer Research and Development Center |
| ET | extra-tropical |
| ETL | Engineering Technical Letter |
| EWL | extreme water level |
| FDEP | Florida Department of Environmental Protection |
| FEMA | Federal Emergency Management Agency |
| FFE | first-floor elevation |
| FIS | Flood Insurance Studies |
| FSS | full storm suite |
| ft | feet or foot |
| ft/yr | feet per year |
| FWOP | future without-project |
| FWP | future with-project |
| G2CRM | Generation II Coastal Risk Model |

| | |
|---|---|
| H&H | hydrology and hydraulics |
| HEC-RAS | Hydrologic Engineering Center’s River Analysis System |
| HURDAT2 | Hurricane Data 2nd Generation |
| IG | infra gravity |
| IH | initial hurricane |
| IOOS | Integrated Ocean Observing System |
| IV | Isla Verde (station number/model reach |
| IWR | Institute for Water Resources |
| lbs/ft3 | pounds per cubic foot |
| LiDAR | Light Detection and Ranging |
| m | meter |
| m/yr | meters per year |
| MHHW | mean higher high water |
| mi | mile |
| mm | millimeter |
| mm/year | millimeters per year |
| mph | miles per hour |
| MSL | mean sea level |
| NACCS | North Atlantic Comprehensive Coastal Study |
| NDBC | National Data Buoy Center |
| NED | National Economic Development |
| NFS | non-federal sponsor |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council |
| NW | northwest |
| OMRR&R | operation, maintenance, repair, replacement, and rehabilitation |
| OP | Ocean Park (station number/model reach designation) |
| OSE | other social effect |
| OWI | Oceanweather, Inc. |
| P&G | principles and guidelines |
| PED | Pre-construction, Engineering, and Design |
| PR | Puerto Rico |
| PR-3 | Puerto Rico Highway 3 |
| PRVD02 | Puerto Rico Vertical Datum of 2002 |
| PSE | protective system element |
| QRA | Qualitative Risk Assessment |
| R | Rincón (station number/model reach designation) |
| RSS | reduced-storm suite |
| SACS | South Atlantic Coastal Study |
| SBEACH | Storm-induced Beach Change |
| SLC | sea-level change |
| SLR | sea-level rise |

| | |
|---|---|
| SPM | Shore Protection Manual |
| STWAVE | Steady-State Spectral Wave |
| SWE | still water elevation |
| TS | tropical storm |
| TSP | Tentatively Selected Plan |
| U.S. | United States |
| UPR | University of Puerto Rico |
| USACE | United States Army Corps of Engineers |
| USGS | United States Geological Survey Agency |
| VLM | vertical land movement |
| WIS | Wave Information Studies |
| WL | water level |
| WRC | Water Resources Council |
| yr | year |

## EXECUTIVE SUMMARY

This appendix represents engineering considerations for the Puerto Rico Coastal Storm Risk Management (CSRM) Feasibility Study (referred to as the Puerto Rico Coastal Study throughout this report). The Puerto Rico Coastal Study, prompted by major Hurricanes Irma and Maria and the resulting Bipartisan Budget Act of 2018 (BBA, 2018), instituted a Tentatively Selected Plan (TSP) that mitigates risk from coastal storms for portions of San Juan and Rincón, Puerto Rico with a federally authorized 50-year (yr) project. The San Juan study area spans from Punta El Medio west to La Ventana al Mar. Existing conditions in San Juan include closed-cell pocket beaches confined by a fringing reef, rocky headlands, and extensive coastal armor. The study area in Rincón spans from Quebrada Los Ramos south to Córcega. Existing conditions in Rincón include a critically eroded shoreline with a continental shelf close to the coast and varying-scale coastal armor (rubble revetments and seawalls) lining most of the shoreline.

Extremely low-lying areas in central Ocean Park to western Isla Verde, surrounded by relatively high upland areas, directed the study to focus on inundation protection measures in San Juan; whereas critically eroded beaches with homes falling into the ocean directed the study to focus on erosion control by acquiring structures in Rincón. Small tides and surge make up still water elevations (SWEs) throughout summer and early fall, but sporadic, intense hurricanes can drastically impact the island during this time. Large, long-period wave events dominate the cooler seasons of the year, primarily from nor'easters in northern Atlantic Ocean latitudes. While nearshore and adjacent features, such as San Juan's fringing reef and Rincón's natural point feature, help to attenuate wave energy, these areas still experience major damages since existing conditions in these communities promote coastal storm risk vulnerability.

USACE, SAJ used four models to quantify the coastal storm risk: SBEACH, Beach-*fx*, the Hydrologic Engineering Center's River Analysis System (HEC-RAS), and the Generation II Coastal Risk Model (G2CRM). The cross-shore change model, SBEACH, yielded storm-induced shoreline erosion for the economic Monte Carlo life-cycle model, Beach-*fx*. HEC-RAS assisted engineers and economists in defining the G2CRM model domain and input. Beach-*fx* determined damages to the first row of structures in the study area, and G2CRM estimated inland structure damages. Future without-project (FWOP) damages and future with-project (FWP) benefits were seamlessly combined from both models in Appendix B: Economic Analysis, where overall benefit to cost ratios (BCR) helped define TSPs with 50 years of federal participation (among other economic and non-economic assessments).

The combined results from the two economic life-cycle models indicate that the "no-action" alternative is the TSP for the Condado and Isla Verde planning reaches, and that the TSP for the Ocean Park planning reach (i.e., central Ocean Park to western Isla Verde – reference Main Report) is focused shoreline armoring at the inundation focal points: Barbosa Park and Marías Skate Park. The TSP in this area consists of a steel sheet pile wall designed with rock armor and a crest elevation of 7 feet PRVD02. The results for the Rincón study area indicate that no-action is the National Economic Development (NED) Plan, but analyses for all four principle and guideline (P&G) planning accounts show this area is underrepresented by just the NED Plan. Thus, the TSP for this area is to acquire structures and property along the shoreline within the study area.

# 1 PROJECT BACKGROUND AND AUTHORITY

The Puerto Rico Coastal Study, completed by the United States (U.S.) Army Corps of Engineers (USACE), Jacksonville District, is intended to determine federal interest over an analysis period of 50 years to address coastal storm risks and to protect the people and infrastructure along portions of the north and west coasts of Puerto Rico. Federal participation determination for this study followed the guidelines outlined in ER 1165-2-130 (USACE, 1989b), which detail the policies for determining the extent of federal participation in potential federal projects for protection from shore erosion, hurricanes, and abnormal tidal flooding that result in damages or losses to coastal resources or development. Further, this study uses the framework of the Shore Protection Manual (USACE, 1984a and 1984b) to assess coastal storm damages and management measures along the shorelines of San Juan and Rincón in Puerto Rico. Since 1930, coastal engineers and scientists affiliated with USACE have conducted coastal process studies and facilitated means to protect shoreline infrastructure and promote coastal community life safety. Early research and experimental centers provided the baseline for what is now known as the Shore Protection Manual (SPM). The SPM is comprised of two volumes. Volume I (USACE, 1984a) introduces coastal processes by defining wave mechanics, water level predictions, littoral processes, and planning analyses suggested to promote coastal community resiliency while maintaining shoreline equilibrium. Volume II (USACE, 1984b) details shore protection features and the structural design of those features in shore protection projects. Notably, the term “tropical system,” consisting of “hurricanes” or “tropical storms,” is comprised of cyclonic events spawning in tropical latitudes, and the term “nor’easter” indicates cyclonic events spawning in northern latitudes.

## 1.1 Study Location and Objective

The Commonwealth of Puerto Rico is an island nation that lies in the northeast Caribbean Sea. BBA, 2018 authorized a federal interest analysis that spanned over 100 coastline miles from the southwest to the southeast corners of the island. Subsequent analyses focused the Puerto Rico Coastal Study on some of the most vulnerable coastal areas prone to inundation, wave, and erosion damages. The non-federal sponsor (NFS) also provided local input to aid the study’s emphasis on areas of greatest importance (see Main Report for additional information on periodic screening efforts). Following the latest scoping after the November 2021 exception request, the study analyzed CSRM for two coastal municipalities: San Juan and Rincón (Figure A-1). The 3x3x3 exception request included four focus areas within both coastal municipalities: Condado, Ocean Park, and Isla Verde in San Juan and Rincón.

Puerto Rico’s most populated municipality, San Juan, is on the island’s northern coast bordering the Atlantic Ocean. Figure A-2 presents the study area, which is in the capital city and includes the 4.3-mile coastal stretch from Punta El Medio (eastern-most point) to La Ventana al Mar (western-most point). Rocky headland points, Punta El Medio, Punta Las Marías, and Punta Piedrita, segment “pocket” beaches (i.e., a generally closed sediment transport cell in the larger nearshore environment) of Isla Verde, Ocean Park, and Condado. Figure A-3 shows the Rincón study area, which spans 1.4 miles from the Rincón floodplain drainage canal, Quebrada Los Ramos (northern-most point), to the small town of Córcega (southern-most point). Rincón, situated on the northwest coast of Puerto Rico, borders the Mona Passage and is primarily known for its coastal recreation and associated tourism. World-class surfing, fishing, and diving are prevalent here, and the famous Tres Palmas Marine Preserve is roughly 0.9 miles north of the Rincón study area. The objective of the Puerto Rico Coastal Study is to assess potential storm damage susceptibility and associated alternative solutions to reduce economic and social impacts from inundation, wave, and erosion damages at these two locations.

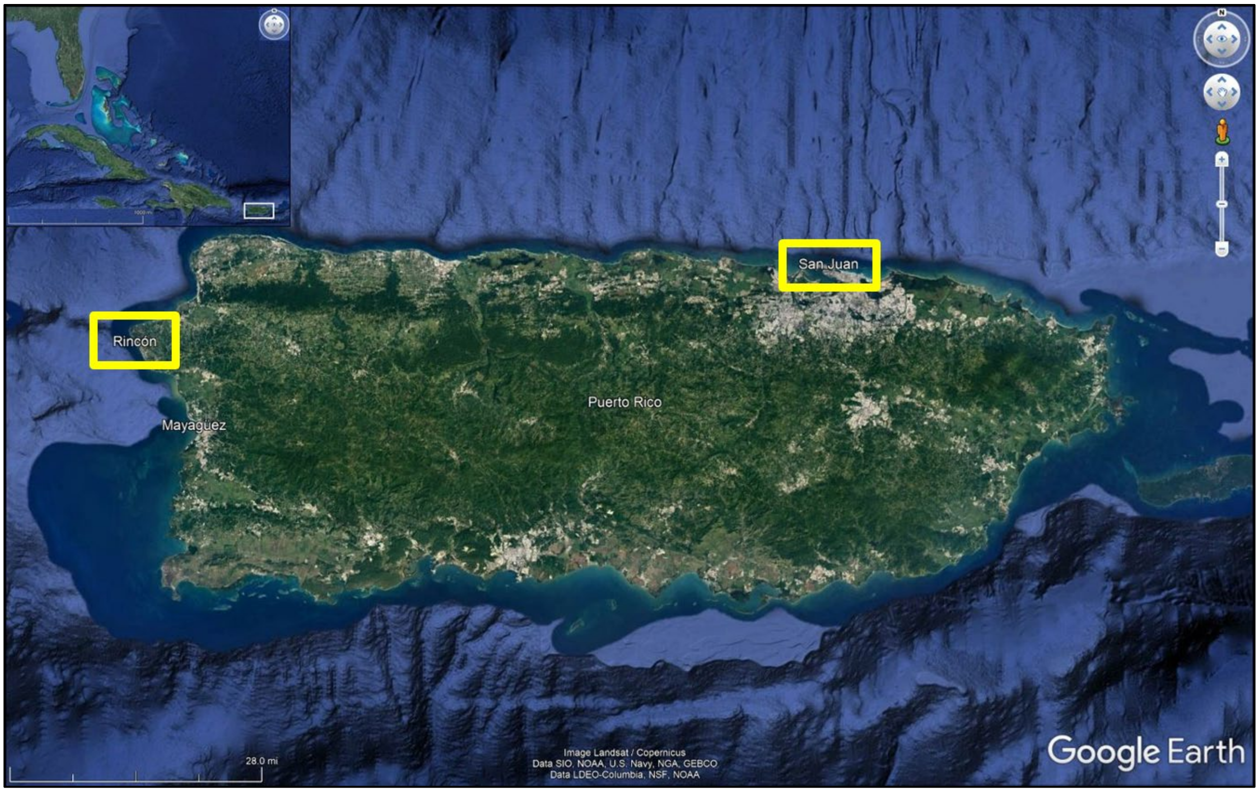


**Figure A-1. Study Area Regional Map**


**Figure A-2. San Juan Study Area Overview**

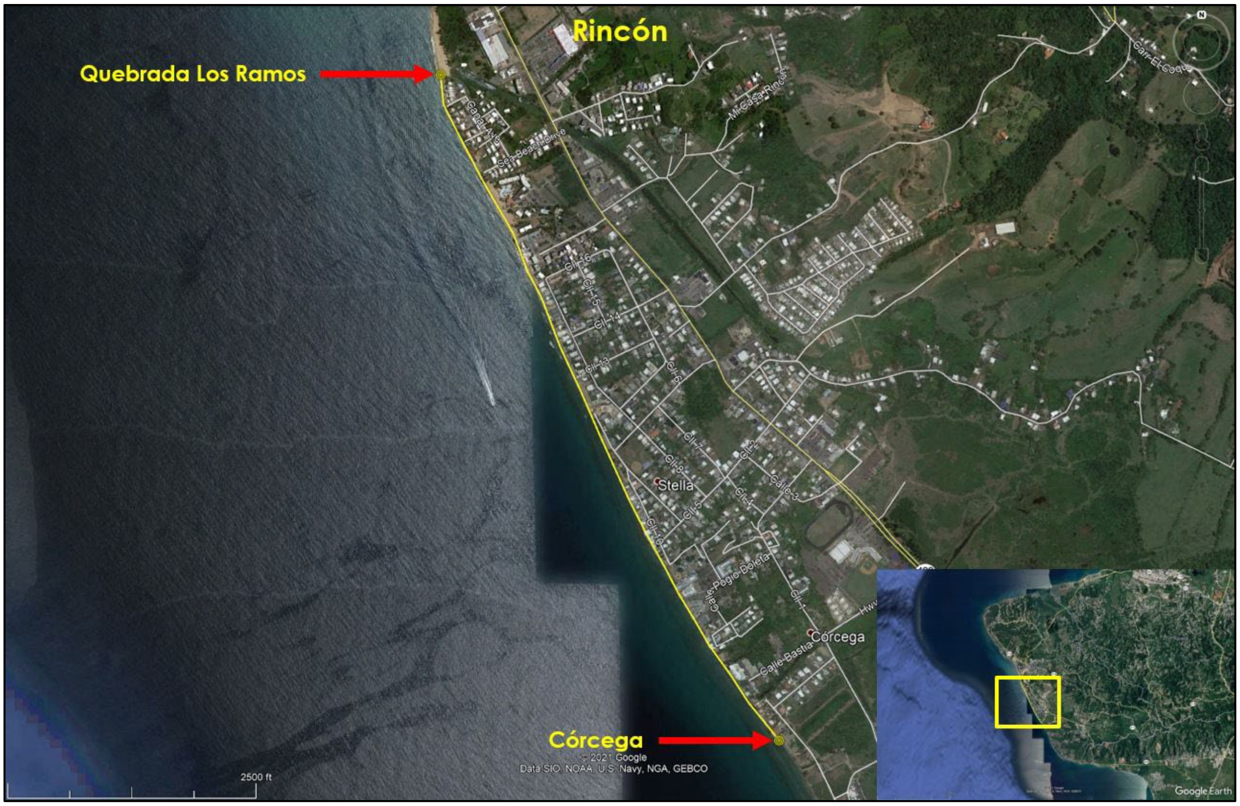


**Figure A-3. Rincón Study Area Overview**

## 1.2 Literature Review

Coastal communities in Puerto Rico have been studied over the past century by government agencies, universities, and independent scientists to ensure coastal resiliency. Federal and non-federal government entities, such as (but not limited to) the Federal Emergency Management Agency (FEMA), USACE, and the U.S. Geological Survey Agency (USGS), have conducted large-scale studies that relied on available data to force coastal models for inundation, wave, and erosion impacts to the communities along coastal municipalities. FEMA's Flood Insurance Studies (FIS) assist communities in the continental U.S. and non-continental U.S. territories in determining coastal community risk to local flood hazards by assessing historic data and performing regional high-fidelity modeling simulations (FEMA, 2012). Some of the more recent FEMA studies conducted in Puerto Rico that include the San Juan and Rincón study areas are the Commonwealth of Puerto Rico and Municipalities FIS (FEMA, 2012), the Post-Hurricanes Irma and Maria Puerto Rico Advisory Data and Products (FEMA, 2018a), and the Puerto Rico Hurricane Evacuation Study Vulnerability Analysis (FEMA, 2018b). USACE has studied (and continues to study) impacts from coastal storms, and USACE designs and implements coastal structures that aim to mitigate risk from these events for coastal communities in Puerto Rico. Previous studies around the current study areas include (but are not limited to) the Detailed Project Report for Boca de Cangrejos, Puerto Rico Section 103 Shore Protection Study (USACE, 1992a), the Caño Martín Peña (CMP) Ecosystem Restoration Study (USACE, 2016), and the San Juan Metro Study (USACE, 2021a). Notable USGS studies for CSRM consideration revolve around beach nourishment sand sourcing for the island's critically eroded beaches and assess island-wide shoreline changes. Kaye (1959), Thieler et al. (1999), and Thieler et al. (2007) are three publications that proved important USGS resources when considering shoreline changes in San Juan and Rincón for the Puerto Rico Coastal Study.

Non-government entities such as (but not limited to) the University of Puerto Rico (UPR) and UPR-Mayagüez and independent research papers have also played an integral role in understanding CSRM in Puerto Rico. Barreto-Orta (1997), Jackson et al. (2006), Bush et al. (2009), Barreto-Orta et al. (2017), Canals-Silander and Rodriguez (2018), Barreto-Orta et al. (2019), Diaz-Velazquez and Canals-Silander (2019), and Mendez-Tejeda (2020) are notable studies that discuss shoreline changes (i.e., shoreline erosion and/or illegal coastal construction built too close to the coast) in and around the San Juan and Rincón study areas and the danger eroding shorelines have to coastal communities during large wave and water level events. Calzada-Marrero (2012), Torruella (2015), Rojas-Vázquez (2016), and Chardon-Maldonado and Canals-Silander (2018) represent a sample of reports that describe important modeling studies and extreme event analysis studies in and around San Juan and Rincón.

The consensus of these existing studies (and others not listed here) is that both San Juan and Rincón coastal communities are vulnerable to coastal storm damages for the following reasons: Illegal or poorly designed permitted structures were built too close to the shoreline that may prohibit natural sand recruitment, a sand deficit partially caused by the excavation of beach and dune sediment from the coast for construction and/or other purposes, and frequent tropical and nor'easter storms that impact the island's coastal communities and degrade the health of natural beaches and coastal structures.

Another important theme in many Puerto Rico publications is the fact that Caribbean islands like Puerto Rico generally lack oceanographic data when compared to locations in mainland United States. Unfortunately, this is not a new topic of discussion among engineers, scientists, and economists working or living in and around Puerto Rico as many of the existing publications listed above, and others like the more recent U.S. Global Change Research Program (2018) climate assessment publication, point out data deficiencies or recommend further data collection and research around the island. Thus, some analyses in this appendix were similarly faced with data deficiency problems like raw extreme event data (i.e., verified extreme water level and wave data) needed for cross-shore change model calibration efforts. Some data gaps were covered through the collection of new data (i.e., environmental and benthic mapping surveys) during the feasibility phase of the overall CSRM process. However, this report recommends future data collection and analyses in the Pre-construction, Engineering, and Design (PED) phase to minimize uncertainty in design parameters before a resulting CSRM project is constructed (refer to Section 5.1.4 and Section 5.2.2).

## 1.3 Existing Coastal Conditions

Physical elevation (topographic, bathymetric, and structure elevations) and observational data (photographs) defined existing conditions for both study areas. These data are necessary to define structure types, to understand potential shoreline evolution and behavior, and to determine how to best set up and simulate cross-shore change and economic life-cycle models. The best available topographic and bathymetric data during initial data collection and model set up efforts were August 2018 Light Detection and Ranging (LiDAR) data from USACE on behalf of FEMA's post-Hurricane Maria data collection work. These data are publicly available at the National Oceanic and Atmospheric Administration's (NOAA) Digital Coast Data Access Viewer website (NOAA, 2021a). Collected and compiled over a 3x3 meter grid, the 2018 LiDAR data were converted into one continuous, regularly spaced elevation surface referenced to a specific horizontal projection and vertical datum for both San Juan and Rincón. These elevation surfaces are commonly referred to as Digital Elevation Models (DEMs), and both San Juan and Rincón DEMs are referenced to the Puerto Rico Vertical Datum of 2002 (PRVD02) and the North American Datum of 1983 horizontal projection. Observation data photographed and referenced in the figures shown in this section are from June 2019 unless otherwise specified. Notable features such as groins, breakwaters, and structure type and condition were documented for the most accurate model setup and results possible. The following sections detail the DEMs and observational data for both study areas.

Coastal conditions continually change over time, and the conditions presented in this section represent the study areas' existing conditions just before modeling and other feasibility study efforts commenced to provide a CSRM plan for both San Juan and Rincón. Sand migrates east and west with seasonal events in the San Juan beaches, so snapshots in time shown in the figures in this section (especially for non-stationary aspects of these beaches like dry recreational beach width) may not be perfectly representative of a future condition.

### *1.3.1 San Juan*

The observations presented here are in order from east to west for the San Juan area, where existing condition photos relate to the stations shown in the first figure of each pocket beach section. The photos within the figures shown in this section were taken in June 2019 (unless noted as a September 2022 condition photo for Ocean Park in Section 1.3.1.2.1). Generally, wider dry beach exists in the central and western portions of the pocket beaches, and hard structures typically line the headlands. Nearshore hardbottom is present along much of the San Juan study area. An offshore and relatively shallow fringing reef is present in front of the four pocket beaches (clearly visible in Figure A-2 and Figure A-4) and is a sharp contrast to the deepest trench in the North Atlantic Ocean, the Puerto Rico Trench, which is directly north of the fringing reef. The trench and offshore fringing reef are important aspects of the San Juan hydrodynamic environment, discussed later in this appendix. The shallow depth of the reef initiates wave breaking and dissipates wave energy propagating toward the coastline, which can be seen even during mild days like in Figure A-2. The headland features segregating each pocket beach largely contain little to no dry beach with nearshore hardbottom and coastal armor (revetments, seawalls, breakwaters, etc.). The central portion of each pocket beach mostly contains dry sand, minimal and intermittent dunes, and little to no dune vegetation.

The DEM shown in Figure A-4 displays important features in the nearshore subaqueous zone and upland terrain for the San Juan study area. As previously noted, a fringing reef is present about 1.0 mile north of the San Juan study area's coastline, which helps dissipate wave energy making its way to the shoreline. However, gaps in the reef (i.e., darker, deeper portions of reef in the figure) expose certain sections of beach to higher wave energy (i.e., Ocean Park versus Isla Verde). The nearshore reef generally mitigates more wave energy around Punta Las Marías, Isla Verde, and Punta El Medio compared to Condado and western Ocean Park where the reef provides less wave attenuation. Figure A-4 also shows that the terrain immediately landward of the beach is higher in elevation (darker red) in places like Condado and western Ocean Park and lower (lighter red) in Ocean Park and east to Punta Las Marías. These gaps in coastal elevation are a flood path that allows ocean water to enter low elevation areas landward of the beach system. Central Ocean Park to Punta Las Marías is especially vulnerable since water has the potential to come from the ocean side and rainfall runoff to compound the risk of elevated water levels in this area.

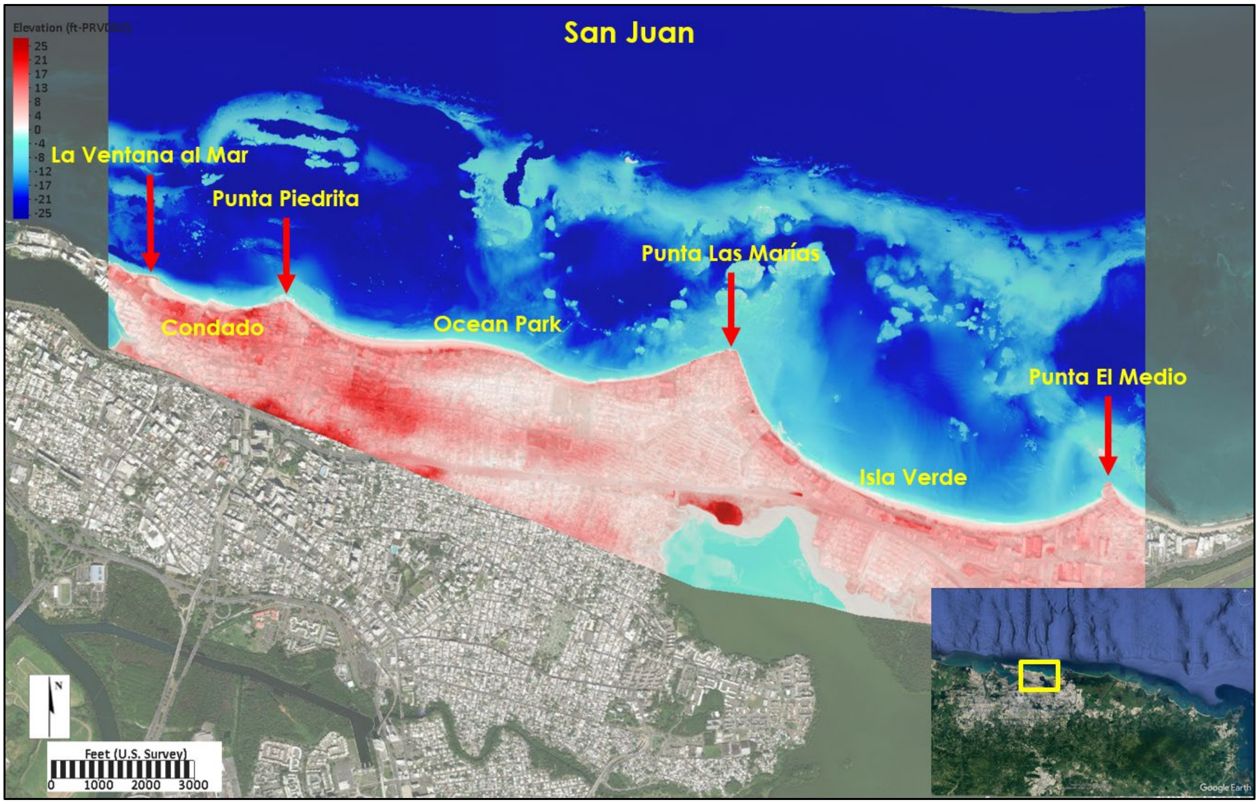


**Figure A-4. San Juan DEM**

1.3.1.1 Isla Verde

The Isla Verde reach extends from Punta Las Marias (west) to Punta El Medio (east), as shown in Figure A-5, and is described using stations IV1 through IV15. Punta El Medio, which segregates Carolina Beach to the east and Isla Verde to the west, contains similar coastline conditions on either side of the headland. Around the Punta El Medio, nothing separates the seawalls and rock revetment from the ocean. A dry, mildly sloping beach generally widens from Punta El Medio traversing west in Isla Verde to stations IV3 and IV4 (the widest portion of dry beach in Isla Verde). Coastal infrastructure in this section is largely unprotected by structures or natural dunes (Figure A-6 and Figure A-7). Consistent conditions from IV3 west to IV6 include a wide and dry beach berm, low-lying infrastructure elevations, and little to no upland inundation protection features (dunes, vegetation, hard structures, etc.), as shown in Figure A-8. The dry beach narrows from IV6 and IV7 to IV12, and upland structure protection largely increases in that area (Figure A-9). IV6 to IV10 contains intermittent dunes and sparse upland vegetation, but coastal construction appears to trend seaward near IV9 and IV10 and terminates in the center of the natural dune line (exposed seawall shown near IV10 in Figure A-10). The diminishing beach width to the west of this area is likely compounded by structures built too close to the coast.

The shoreline from IV12 to IV14 consists of a detached rock breakwater with three small rock groins in the nearshore zone, large seawalls, and small rock riprap protecting upland coastal structures. Wave energy and current circulation patterns appear to impact these structures during large events, as a portion of seawall is undermined, and riprap rock is displaced near IV13 (Figure A-11).

West-northwest of IV14 is likely the most critically exposed portion of Isla Verde. According to locals, coastal high-rise development between IV14 and IV15 terminated in the early stages of construction, and the area was abandoned. A small seawall protects the coastline between IV14 and IV15 but is actively overtopped during low-energy, wind-driven waves. Overtopping and wave reflection from the seawall may actively promote erosion on either side of the seawall. Rock riprap generally protects the coastline west-northwest of IV15 in western Isla Verde.

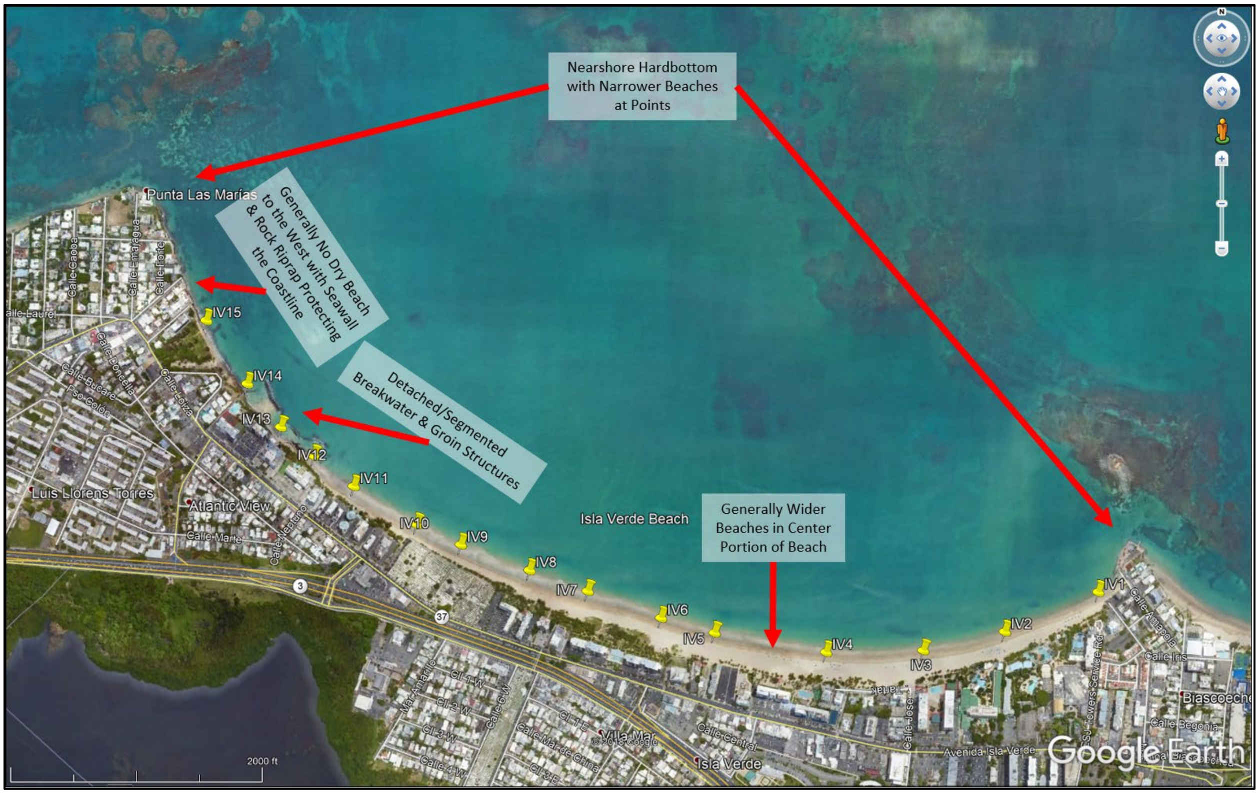


**Figure A-5. Isla Verde Areas of Interest**


**Figure A-6. Western Punta El Medio in Isla Verde near IV1 (Top) and IV3 (Bottom), Facing East**


**Figure A-7. Existing Coastal Conditions near IV3/IV4 (Top is Facing West and Bottom is Facing South)**


**Figure A-8. Decreasing Beach Widths and Increasing Flood Protection near IV6/IV7, Facing West**

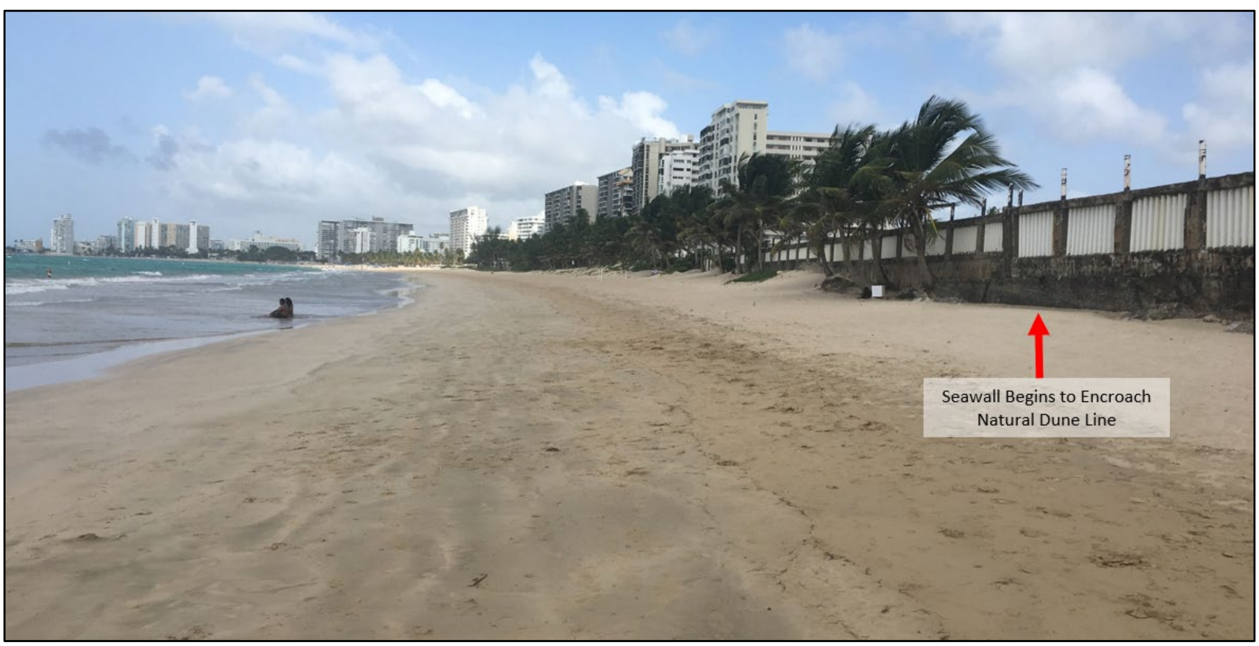


**Figure A-9. Upland Seawall near IV10, Facing East**


**Figure A-10. Seawalls near IV13, Facing West**

**Figure A-11. Breakwater and Groins from IV12 to IV14, Facing Northwest (Left) to Southeast (Right)**

#### 1.3.1.2 Ocean Park

Figure A-12 shows a general Ocean Park coastal area overview. Like Isla Verde, the eastern and western beach extents of Ocean Park contain little to no dry beach with prevalent nearshore hardbottom and a wider central beach expanse. Punta Las Marías is the point that segments Isla Verde to the east and Ocean Park to the west. It resembles Punta El Medio by largely containing seawalls and rock riprap protecting upland structures from inundation, erosion, and wave attack.

Nearshore hardbottom is exposed at low tide east of station OP5, and a narrow, mildly sloping beach berm, with no dune or upland vegetation, adjoins hard coastal structures in small sections between OP1 and OP5 (Figure A-13). The small beach between OP1 and OP5 is largely seasonal or ephemeral. The seawalls in this area are relatively large, and storm drain culverts exist within the seawalls that could act as focal points for flood waters during costal storms, which could pose major dune and berm erosion problems if nourishment is constructed in this area. Additionally, the seawalls appear to have an adverse effect on sand retention in this area (i.e., even with a large recovery timeline, it's unlikely a large beach would exist in this area given the encroaching development and large seawalls that reflect much of the incident wave energy). The coastline between OP5 and OP7 is somewhat unique to Ocean Park as it contains the only stretch that is not developed with homes or condominiums. This area, Barbosa Park, is historically known for extensive coastal inundation since storm surge and wave attack can focus on this unprotected stretch of coast. Hard structures to the east and west may focus coastal water energy, promoting surge waters to follow the path of least resistance at Barbosa Park as it propagates landward. Energetic conditions have eroded fronting beaches (at OP5 and OP7), and the berm crest is set back at the center of the park, just west of OP6. At the time of inspection (June 2019), erosive coastal forcing formed a large scarp near OP5 and OP6, exposed nearshore hardbottom, and undermined the eastern edge of the seawall protecting western Calle Park Blvd. A mixture of riprap and concrete placed at the northwestern corner of the road's seawall is likely an emergency measure to protect upland public property. Additionally, sheet pile seawall remnants are buried in the beach berm near OP7. Figure A-14 shows the concaved beach with structures on either side of the park expanse. More recent site visits (September 2022) indicated increased erosion along the areas east and west of Barbosa Park with virtually no dry beach. The beach erosion appeared to result from waves impacting the existing seawalls unimpeded (due to the lack of dry beach) and increased erosion and longshore transport conditions from the reflected wave energy. These erosive conditions are expected to worsen the longer the seawalls are exposed and therefore, decrease the potential of a wide and dry beach naturally returning.

Contrary to the aerial shown in Figure A-12, the shoreline from OP7 to OP8 is extremely eroded, and ocean waters regularly impact the seawalls protecting upland structures (Figure A-15). The beach width increases from OP8 to its widest point in Ocean Park near OP11. Sparse dunes with upland vegetation are present between OP10 and OP11. However, this feature likely would not impede flood waters during a storm event as water could traverse through dune gaps and impact upland structures if the upland elevations are not at sufficient elevations. Figure A-16 shows the features from OP8 to OP11.

The beach width generally decreases from OP11 to OP16. Lack of dunes and upland vegetation and two storm drain runoff culverts that terminate in the berm near OP12 and OP14 all likely accentuate flood risk potential in this area (Figure A-17). The narrowing beach berm at the western end of Ocean Park Beach near Punta Piedrita (the point at the western end of Ocean Park) is synonymous with the other beaches' extremes – nearshore hardbottom is exposed, and ocean waters regularly encroach towards upland structures. Further, the relatively small seawall protecting condominiums at Punta Piedrita has failed, and concrete debris is scattered in the nearshore zone.

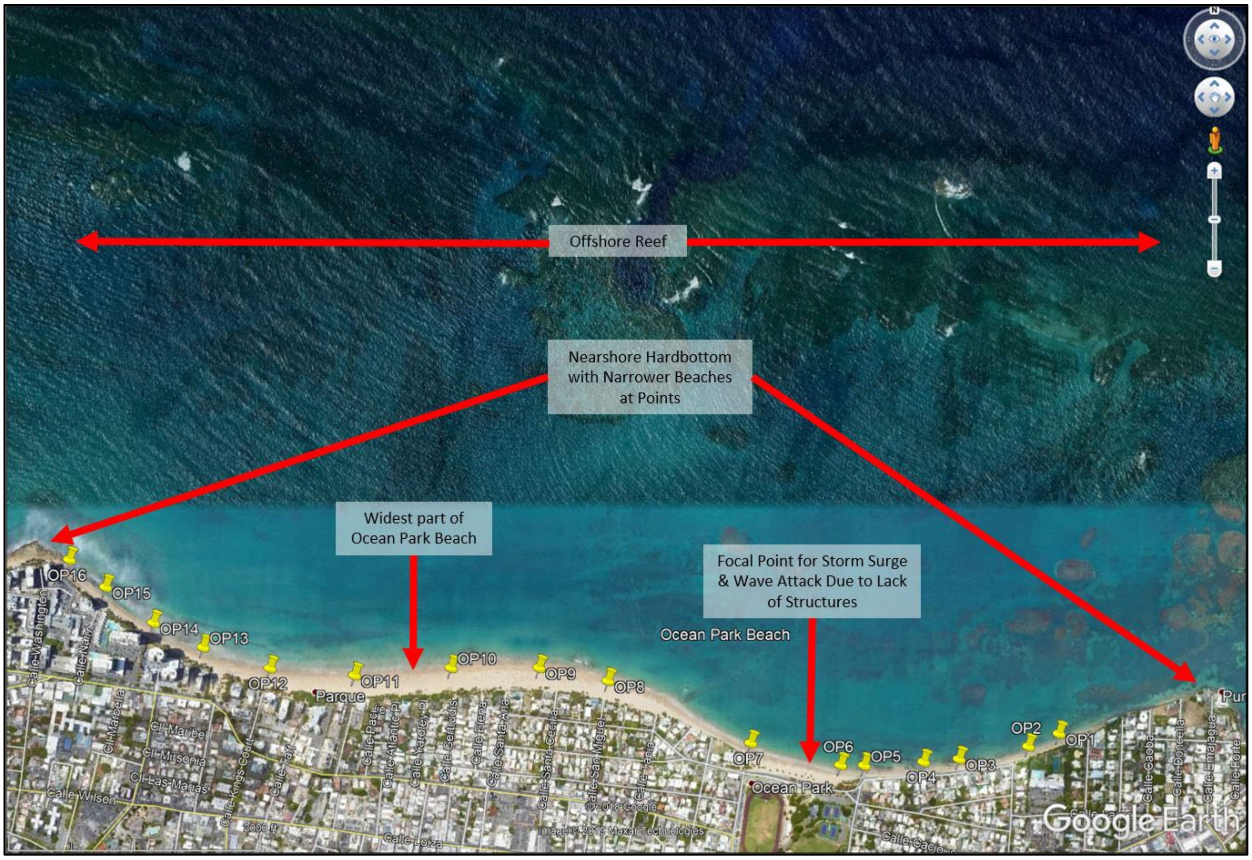


**Figure A-12. Ocean Park Beach Areas of Interest**


**Figure A-13. Eastern Ocean Park Beach near OP1 (Top) and OP5 (Bottom), Facing East**

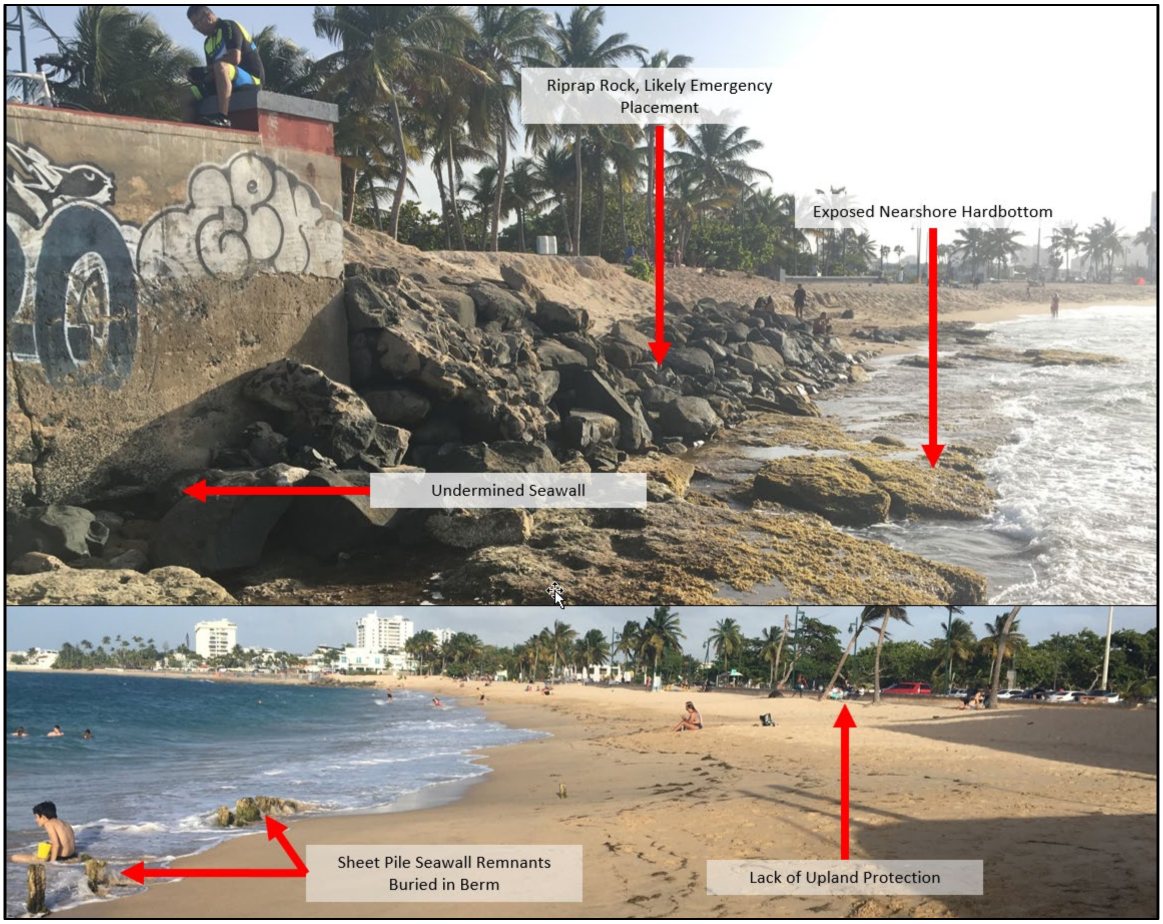


**Figure A-14. Ocean Park near OP5 (Top, Facing West) and OP7 (Bottom, Facing East)**

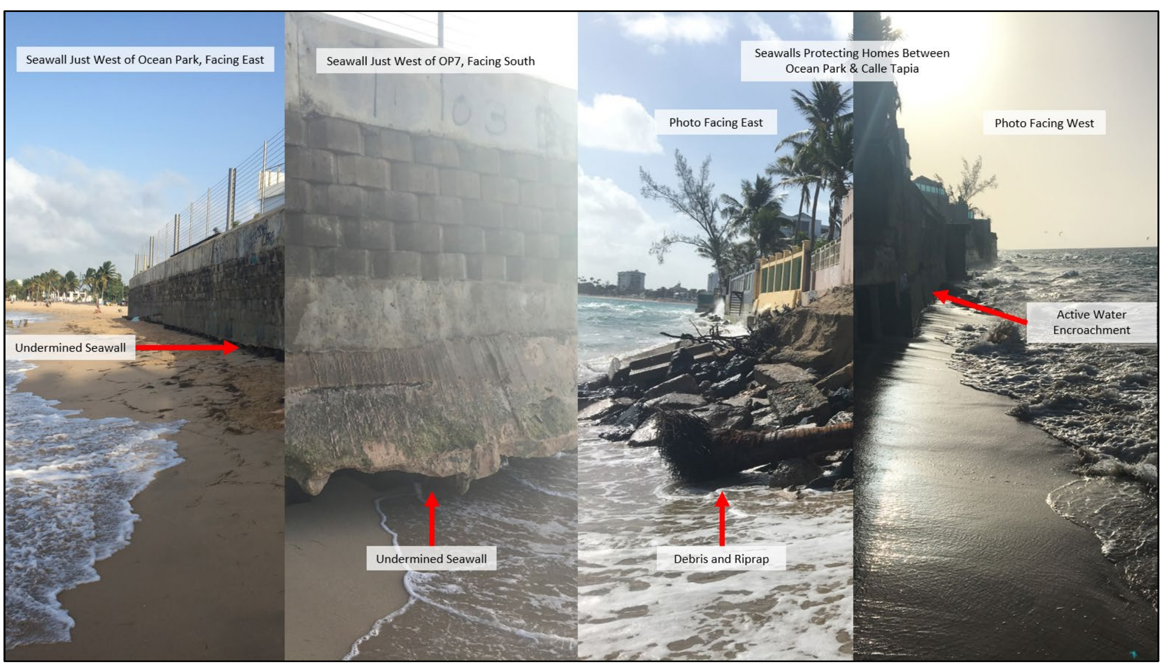


**Figure A-15. Ocean Water Encroachment and Undermined Seawalls Just West of Ocean Park**


**Figure A-16. Widening Beach Traversing West from OP8 to OP11**


**Figure A-17. Western Ocean Park Beach from OP12 to OP16**

#### *1.3.1.2.1 Shoreline Change Hot Spot*

As previously mentioned, existing condition data (survey data and observational data) presented in Section 1.3 represent a snapshot in time. While this is required to identify study site characteristics and develop existing condition model input, short- and long-term changes to the system need to be identified to accurately estimate future condition coastal storm impacts. One area within the San Juan study area that has gained considerable public attention is a shoreline change hot spot in central Ocean Park. Shoreline hot spots are sections of beach that accumulate or lose sand more rapidly than other sections of adjacent coastline. One can identify erosional hot spots as rapid dry beach cross-shore width changes or rapid volume fluxes. They can occur on natural shorelines or beaches that have synthetic nourishment that has been introduced into the system, and Dean and Dalrymple (2002) note that hot spots occur to some degree on all nourished beaches. Bridges and Dean (1996) offer potential reasons for hot spots to occur, two of which may be important in Ocean Park: headland effects and 'structures such as seawalls' close to the shoreline.

In recent years, private homeowners and government entities have documented a shoreline hot spot in central Ocean Park westerly-adjacent to Barbosa Park. Significant fluctuations of beach volume have been documented from 2016 to 2022 from western Barbosa Park (OP7) to Calle Santa Ana (west of OP9), where major shoreline erosion was noted in this area in summer 2019, 2021, and 2022. Short-term dry beach changes are heavily influenced by seasonal forcing in this area (Section 2.1). Satellite, aerial, and other data indicate that if berm losses occur at one end of a pocket beach in San Juan, the other end of that pocket beach generally incurs commensurate berm advancement and vice versa. A review of periodic Google Earth (2022) satellite imagery indicates that seasonal cross-shore shoreline position changes in this area, of around 150 feet, are not uncommon (Table A-1 and Figure A-18). However, these short-term fluctuations are not confined to shoreline or overall volume erosion. Table A-1 shows shoreline erosion across all measured cross-sections from April 2016 to September 2019, but shoreline advances between September 2019 and July 2020 are conversely documented.

Diaz and Canals (2019) also present an analysis of the Ocean Park hot spot, where severe shoreline erosion in this area's summer 2019 shoreline position was the focus of the report. Subsequent personal communication confirmed this beach partially recovered later that year and through 2020 as indicated in Table A-1, then eroded severely through summer 2021 and oscillated similarly through summer 2022. Accretion in the Ocean Park hot spot, after a period of sediment loss without an updrift feeder beach to replenish the system, indicates a closed-cell system between headland points. Shoreline erosion may be exacerbated due to hard shoreline construction in the area (seawalls noted previously) and storm seasonality (more tropical events and less nor'easters which naturally push this material back. The shoreline erosion will likely worsen if the seawalls and structures are exposed for longer periods of time. Figure A-18 shows that while shoreline positions migrated landward west of Barbosa Park, beaches closer to Punta Piedrita experienced commensurate shoreline advancement at the same time. Comparing USACE LiDAR DEMs from February 2016 to August 2018 (Figure A-19) indicates similar net-zero volume loss outside the Ocean Park pocket beach sediment transport cell, where red contours indicate net accretion and blue contours indicate net erosion.

Data used in USACE feasibility studies favor long(er)-term changes to yield historic erosion or accretion trends to project future shoreline behavior. Thus, the long-term shoreline changes described in Section 2.2.2 were used in general modeling efforts, but model sensitivity simulations were completed to ensure the noted hot spot does not impact overall CSRM design effectiveness. Sensitivity results are noted in Section 4.6.

**Table A-1. Estimated Shoreline Change from First Row of Coastal Structure Seaward Point**

| Date (Line Color) | Cross-Section Alignment X0 (ft)[1] | Cross-Section Alignment X1 (ft)[1] | Cross-Section Alignment X2 (ft)[1] | Cross-Section Alignment X3 (ft)[1] |
|---|---|---|---|---|
| Distance Baseline (Yellow) | 0 | 0 | 0 | 0 |
| April 2016 (Peach) | 200 | 150 | 100 | 50 |
| August 2018 (Black) | 140 | 100 | 65 | 20 |
| September 2019 (Green) | 40 | 0 | 0 | 0 |
| July 2020 (Blue) | 125 | 90 | 45 | 10 |

[1]Measured shore perpendicular along blue cross-section lines from yellow structure line in Figure A-18.

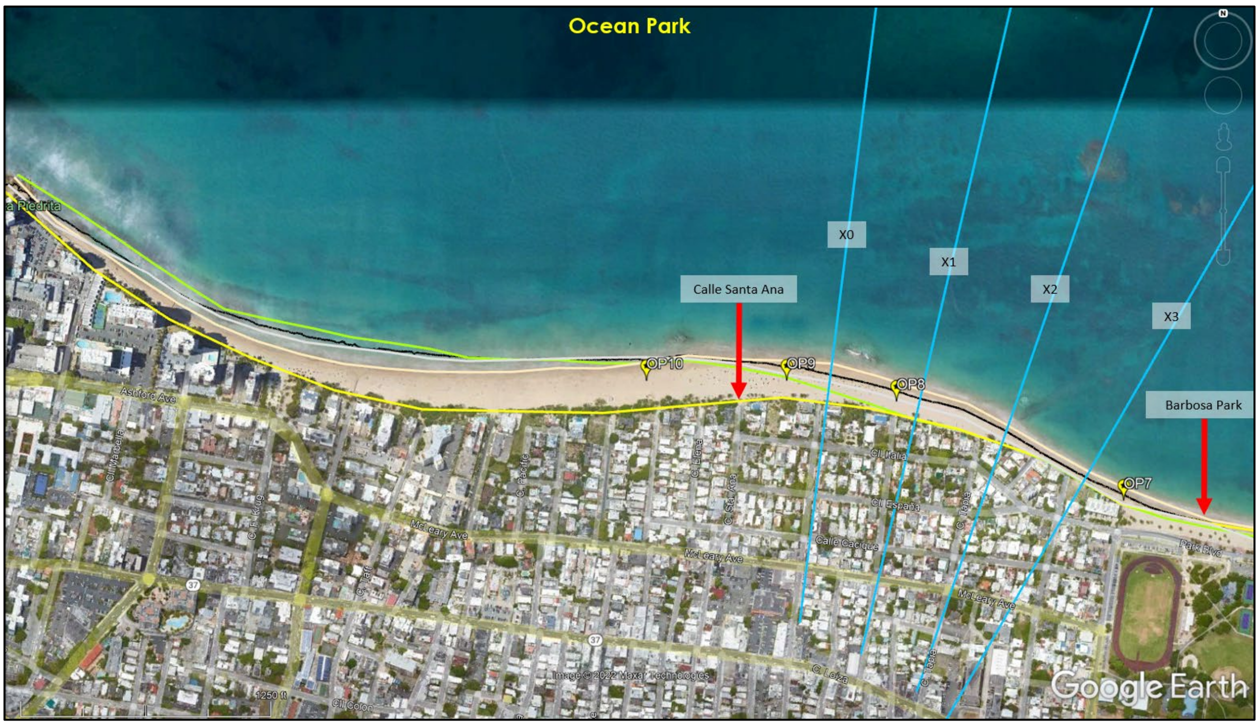


**Figure A-18. Estimated Shoreline Change from First Row of Coastal Structure Seaward Point**

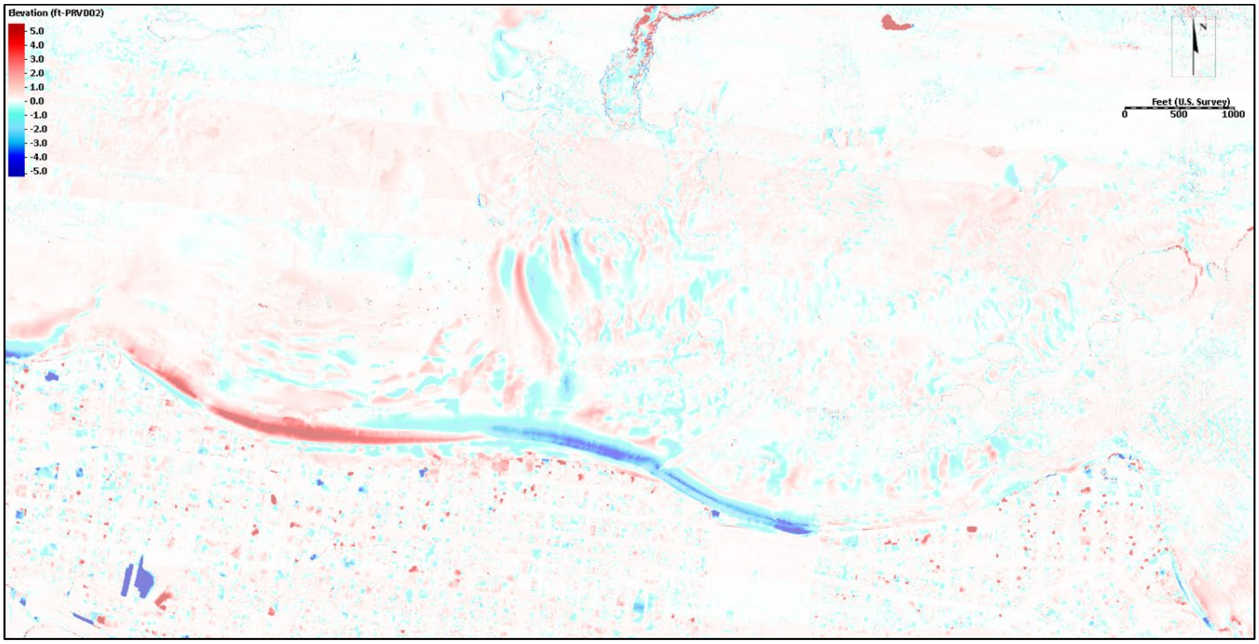


**Figure A-19. Volume Changes in Ocean Park from February 2016 to August 2018**

#### 1.3.1.3 Condado

Condado contains the smallest area of dry beach out of the three San Juan beaches, detailed in this report, as indicated in Figure A-20. The eastern 0.5 miles from Punta Piedrita near station CO1 west to the inclined groin at La Ventana al Mar, CO8 to CO9, encompasses nearly all the dry beach in this expanse, where the widest part of the beach is centered around a small, porous groin at CO5. The western 0.5 miles from the angled groin to El Boquerón contain virtually no dry beach, and waves regularly break directly on exposed nearshore reef, seawalls, and rock revetments.

The beach berm width generally increases from CO1 to CO5, where virtually no dry beach exists east of CO4. Exposed nearshore hardbottom adjoined large condominium seawalls, and two road runoff culverts drain rainwater from roads to the ocean in this portion of beach (Figure A-21 and Figure A-22). Conversely, structures between CO4 and CO7 largely contain first-floor elevations in line with the flat beach berm crest without soft or hard shoreline protection; additionally, a shore-perpendicular groin is at CO5 (Figure A-22 and Figure A-23). A large, inclined, and shore-parallel groin protects the shoreline from CO7 to CO9. The roughly 500-foot-long, 50-foot-wide groin consists of large, rock riprap surrounding a recreational concrete cap walkway. Damaged railings on the boardwalks shown in Figure A-24 are likely a result of recent, major storm impacts.

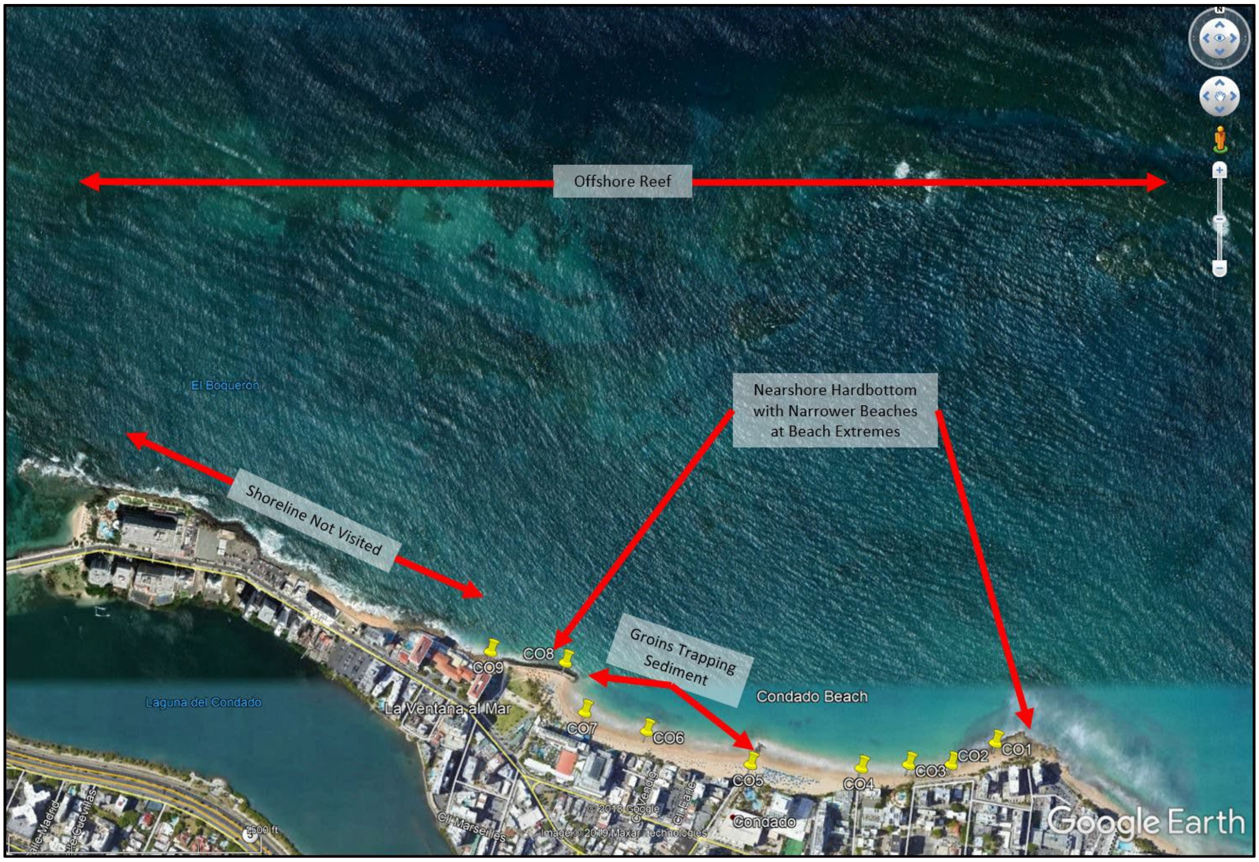


**Figure A-20. Condado Beach Areas of Interest**

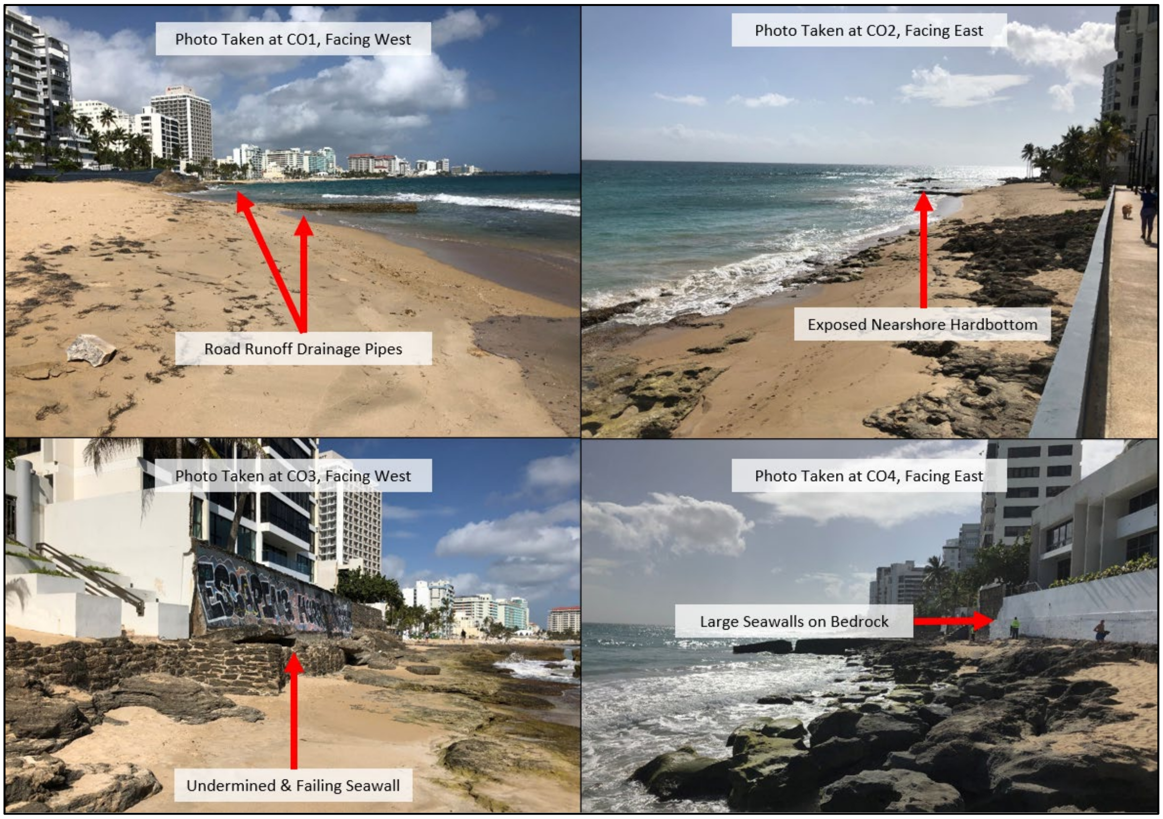


**Figure A-21. Eastern Condado Beach from CO1 to CO4**

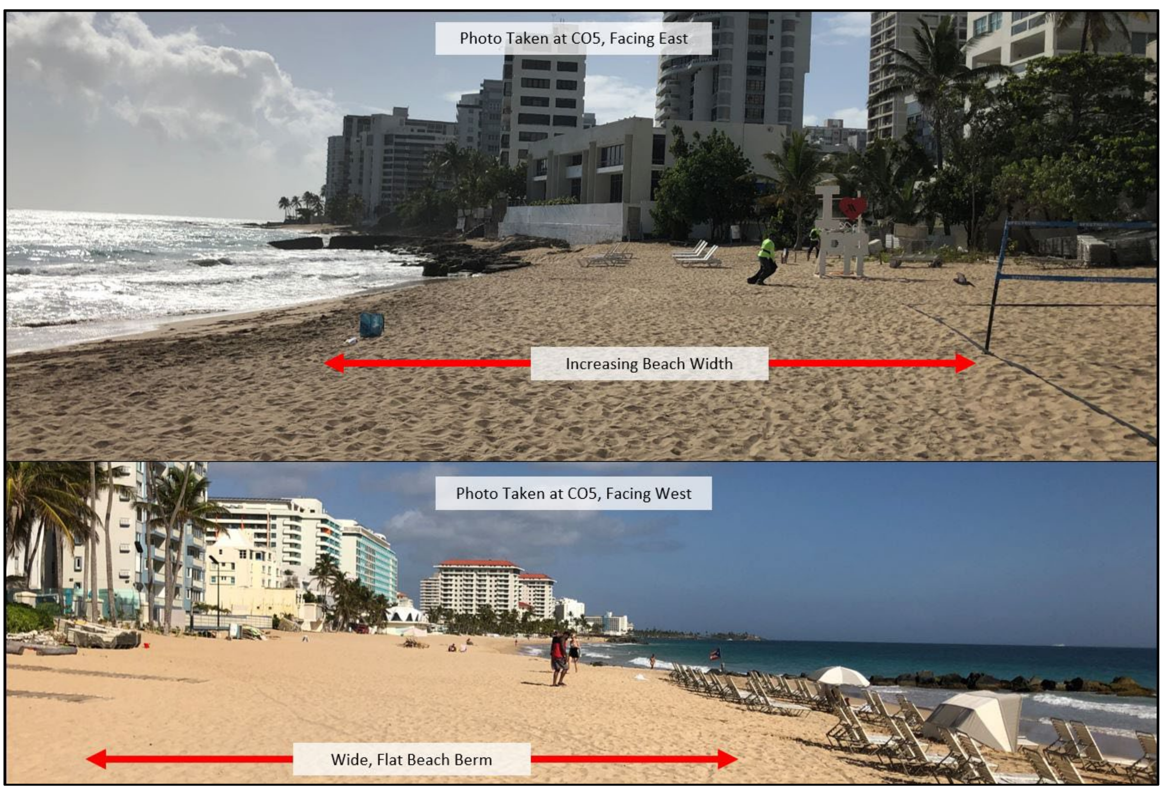


**Figure A-22. Eastern Condado Beach at CO5**


**Figure A-23. Eastern Condado Beach from CO6 to CO7**

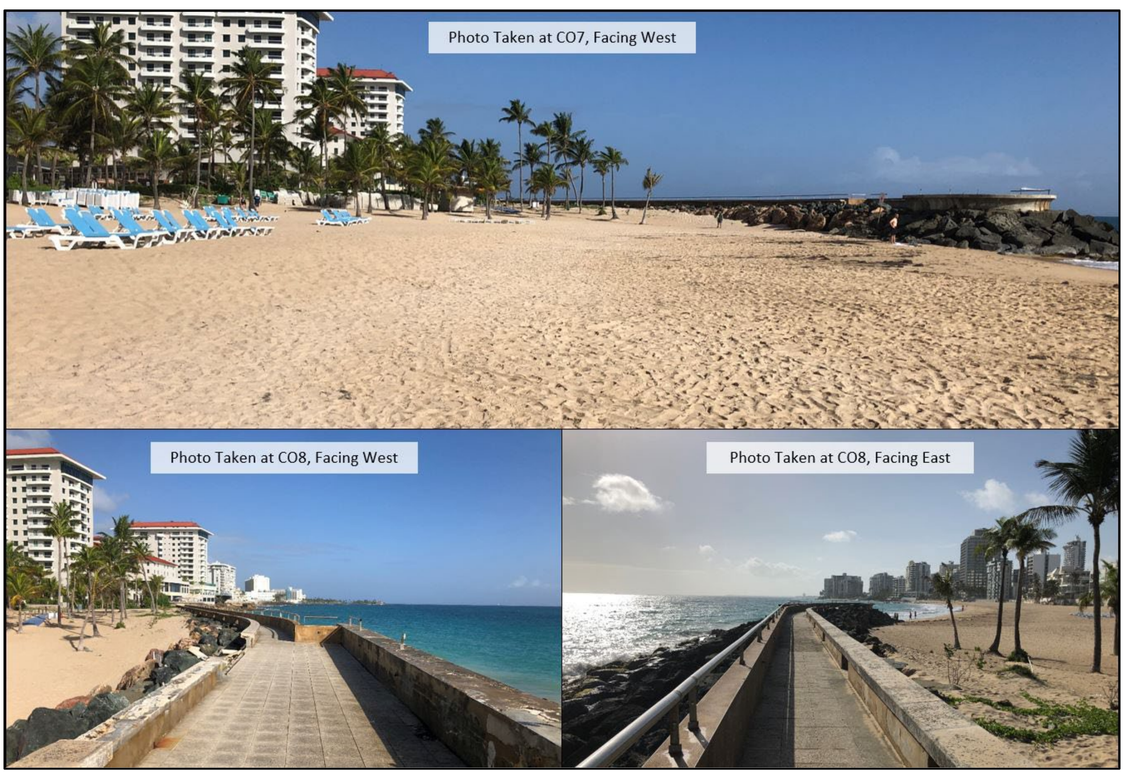


**Figure A-24. Eastern Condado Beach from CO7 to CO8**

### *1.3.2 Rincón*

The Rincón DEM shown in Figure A-25 is from the same source as the San Juan DEM from Section 1.3.1 and displays important features in the nearshore subaqueous zone and upland terrain for the Rincón study area that spans from Quebrada Los Ramos to Córcega. The continental shelf is much closer to the Rincón study area coastline than noted in San Juan, which could exacerbate wave impacts between Quebrada Los Ramos south to Córcega. A prominent marine preserve, Tres Palmas, is an important natural resource roughly 1.0 mile north of the study area and is a nearshore feature that one must consider when implementing CSRM alternatives for environmental reasons. Bajo Blanco, a very shallow sand shoal, is immediately north of the study area. Quebrada Los Ramos is the canal at the northern end of the study area that acts as the main waterway that drains upland rainfall to the ocean. This canal can be free flowing during high-wave events on the ocean side or during high rainfall events on the landward side; however, it was blocked with sediment during the 2019 site visit. Terrain elevation in the general area is relatively consistent throughout the study area at around 7.0 to 9.0 feet PRVD02, but mountainous terrain northeast of the study area could exacerbate inundation along the coastline during coastal storm events if ocean waters and rainfall runoff yield compound flooding.

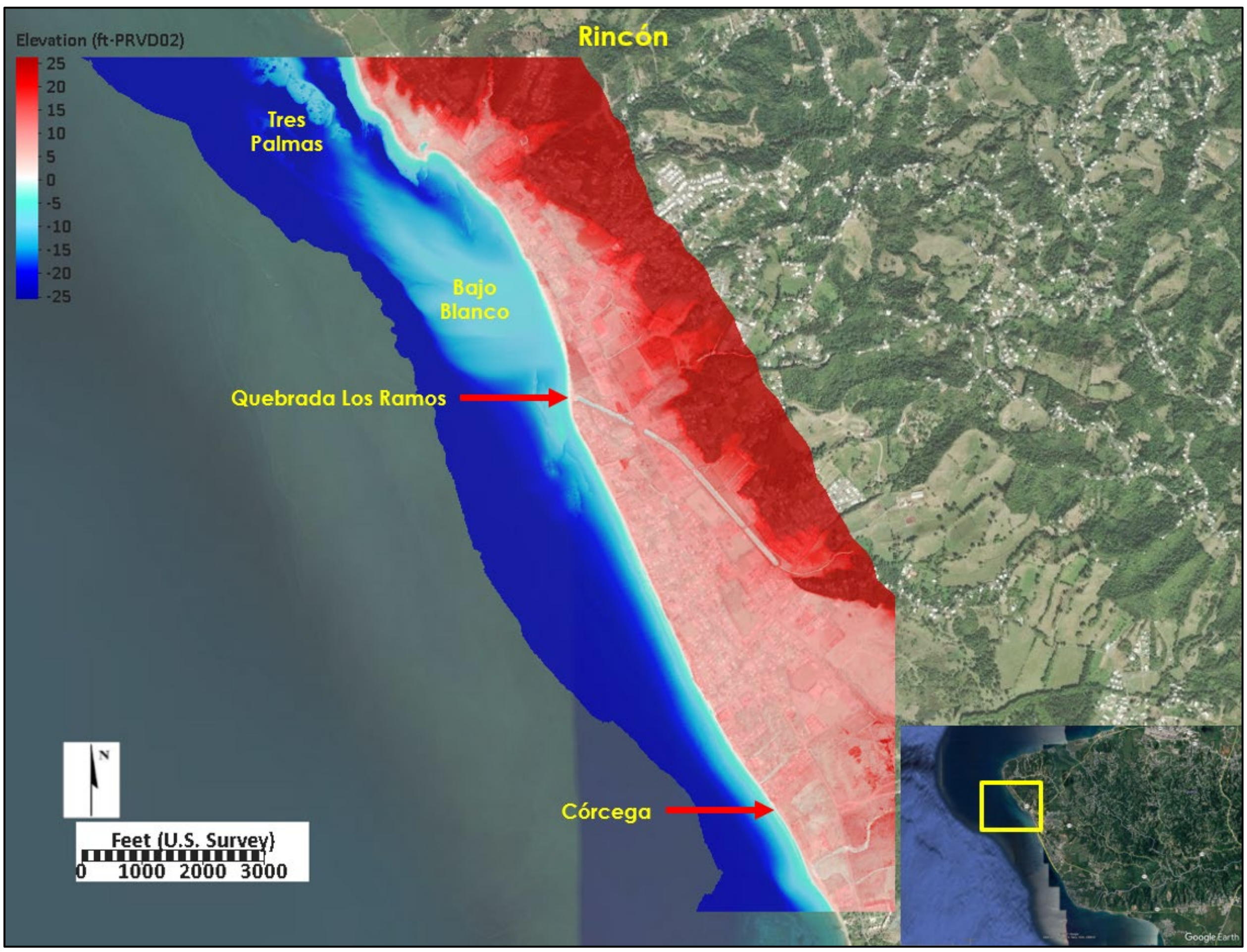


**Figure A-25. Rincón DEM**

The observations presented here are in order from north to south for the Rincón study area. The shoreline from Quebrada Los Ramos to Córcega generally consists of coastline with minimal to no dry beach. Homes and hotels may have been built too close to the coastline in this area as pockets of dry beach only exist where structures are set back from the shoreline. Visible nearshore hardbottom begins just north of photo location R9, shown in Figure A-26, and was largely exposed after Hurricane Maria and Nor'easter Riley in fall 2017 to spring 2018 based on local communication and Google Earth Imagery analyses. Structures to the south (especially in Córcega) are regularly impacted by storm waves and water levels and are either undermined with failed foundations or protected by emergency riprap placement. Seawalls and revetments in front of homes and hotels protect many of these structures. Additionally, many structures in Córcega appear abandoned. Figure A-27 through Figure A-31 depict the area south of Quebrada Los Ramos.


**Figure A-26. Rincón Areas of Interest**


**Figure A-27. Rock Revetment and Debris in front of Small Seawalls near R6/R7**


**Figure A-28. Active Water Encroachment to Seaward-Most Structures near R8/R9**


**Figure A-29. Visible Nearshore Hardbottom near R9**


**Figure A-30. Small Beaches Exist Where Structures Are Set Back from the Coast near R10**

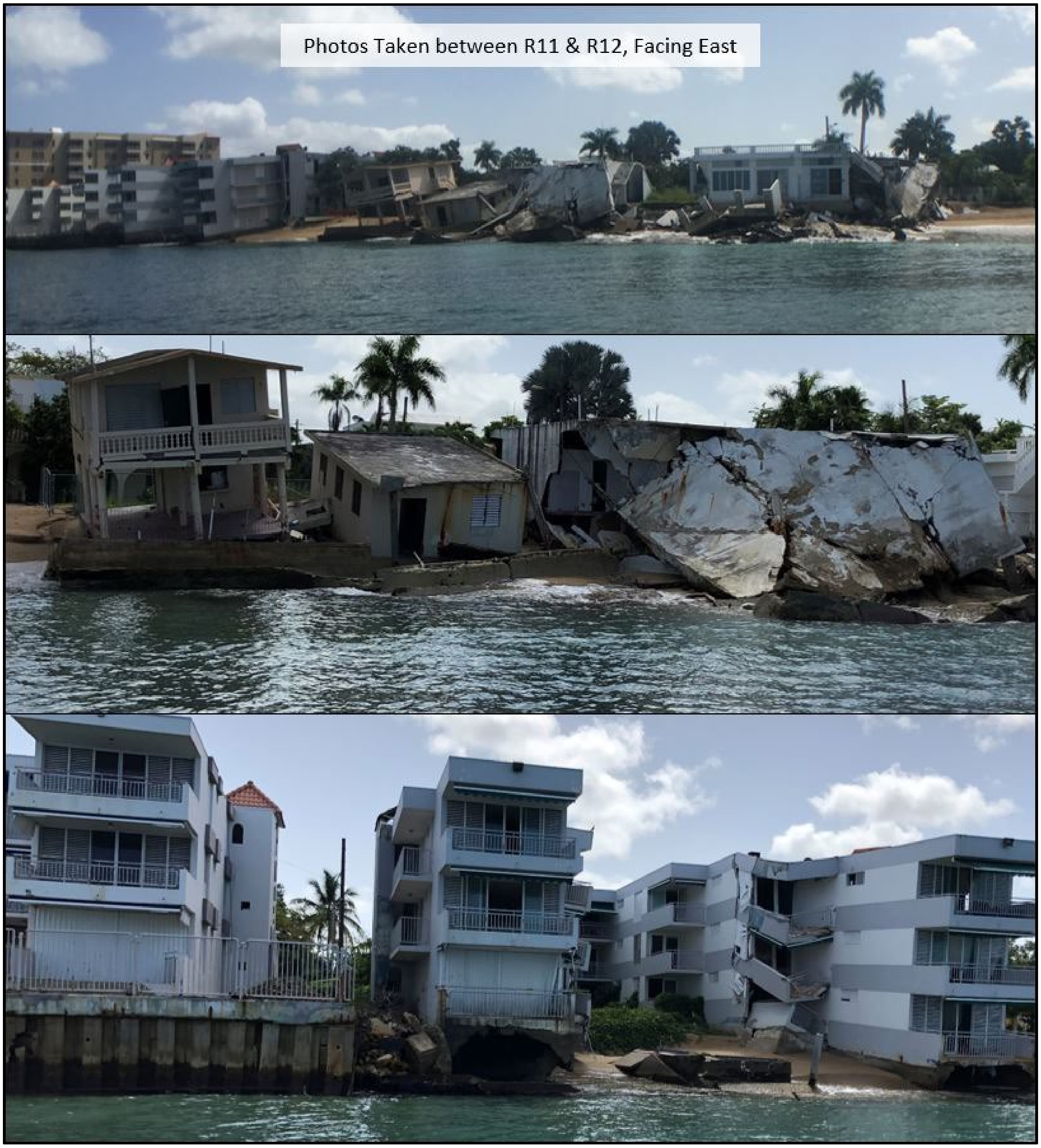


**Figure A-31. Destroyed Homes and Active Water Encroachment in Stella and Córcega**

# 2 COASTAL HAZARDS IN PUERTO RICO

Natural coastal hazards can be broken down into two categories: short- and long-term processes. Understanding how to quantify and efficiently mitigate the threat posed by coastal hazards is vital to the resilience of coastal communities. Short-term coastal events reside on a temporal scale of days, hours, or sometimes even minutes. These events include tides (high tide amplitudes), wind, waves, and tropical and nor'easter storm surge. Accurately quantifying possible flood and erosion thresholds due to these constituents can be accomplished by using different computational modeling suites (Bredesen, 2015). Long-term processes act over a period of months, years, decades, or longer. Long-term coastal processes include seasonal flow and sediment transport patterns, relative sea-level change (SLC), and long-term shoreline evolution. Short- and long-term events, and the hazards that result from these events in Puerto Rico, are the focus of this appendix.

## 2.1 Short-Term Coastal Processes

The most destructive coastal hazard in Puerto Rico is a tropical system. Warm ocean waters evaporate in tropical latitudes, condensing to form clouds (USGS, 2014). Warm air continues to rise causing atmospheric pressure to drop due to less air mass at the ocean's surface. The pressure differential and energy transfer from the condensation result in cooler air temperatures that blow from high to low pressure, creating a circular "eye" of the newly formed storm system. The cooler air subsides slowly within the eye-wall region before rising again. This process forms winds that rotate counterclockwise in the northern hemisphere due to the earth's rotation on its axis. The storm intensifies, using the latent heat from warm tropical waters as an energy source (Bredesen, 2015). Three of the most notable hurricane events in Puerto Rico in the last century include Hurricane Georges (1998), Hurricane Hugo (1989), and Hurricane Maria (2017). These events battered the island with intense winds, heavy rain, large waves, and a relatively large storm surge.

Atmospheric variations in the northern hemisphere's winter months can cause nor'easters that are coastal cyclonic storms that rotate counterclockwise in a low-pressure system around a central low-pressure extreme that are generally in higher latitudes than hurricanes (Bredesen, 2015). Depending on the nature of the event, nor'easters can impact extensive spans of the Puerto Rican coastline with days of large and long-period waves while spinning thousands of miles away (no direct wind and rain impact). While the Puerto Rico Coastal Study focuses on CSRM efforts, two coastal storms components that are not directly considered are direct wind impacts and rainfall. Additionally, the short-term coastal process of astronomical tides can exacerbate flooding caused by both tropical systems and nor'easters. The primary purpose of the Puerto Rico Coastal Study is to reduce impacts from erosion, surge, and wave events associated with tropical and nor'easter events; interior drainage for rainfall is outside the scope of this study.

### *2.1.1 Astronomical Tides*

Astronomical tides fluctuate due to the gravitational influences of the moon, the sun, and the earth. Tides are generally well understood and relatively easy to predict from established astronomical tidal constituents. NOAA regularly publishes tide tables for selected locations along coastlines around the world. These tables provide times of high and low tides as well as predicted tidal amplitudes that aid in coastal study's modeling and design efforts.

#### 2.1.1.1 Tides in San Juan

Tides in San Juan, Puerto Rico are mainly affected by mixed semidiurnal tidal fluctuations of the Atlantic Ocean with two high tides and two low tides that occur at different elevations per tidal day. Tide phases and amplitudes in San Juan are available at the NOAA tide station 9755371 (San Juan, La Puntilla) in the San Juan Bay as shown in Figure A-32. The NOAA tide gauge presently contains astronomical tide data since November 1977. Tidal datums for the San Juan study area are referenced to PRVD02 from the tidal epoch period of 1983 to 2001, are based on a discontinuous, 17-year analysis period, and have a mean tidal range of 1.11 feet (Table A-2). The PRVD02 vertical datum is the official vertical datum of Puerto Rico and will be used as the referenced datum in most of this report.

PRVD02 was created via a geodetic leveling network based on the relation between a stationary point (a benchmark) and the mean sea level (MSL) datum at that benchmark (NOAA, 2012). Therefore, MSL is a datum related to average local water levels around a tide station (may change by location), but PRVD02 is an island-wide, stationary, geodetic datum as a part of NOAA's overall National Spatial Reference System (NOAA, 2012). The San Juan NOAA tide station 9755371 hosts the benchmark used in this effort; thus, PRVD02 and MSL should always be equal in San Juan, Puerto Rico. Some figures represented in this report may reference MSL instead of PRVD02 for this reason.


**Figure A-32. NOAA Tide Stations with Long-Term Records in the Vicinity of San Juan, Puerto Rico**

**Table A-2. San Juan Tidal Datums (NOAA Station 9755371)**

| **Location: 18° 27.6' N, 66° 7.0' W<br>Analysis Periods: Jan. 1983 - Dec. 1987, Jan. 1990 - Dec. 2001** | |
|---|---|
| **Datum** | **Elevation (feet PRVD02)** |
| Mean Higher-High Water | 0.81 |
| Mean High Water | 0.55 |
| Puerto Rico Vertical Datum of 2002 | 0.00 |
| Mean Sea Level | 0.00 |
| Mean Low Water | -0.56 |
| Mean Lower-Low Water | -0.76 |

#### 2.1.1.2 Tides in Rincón

Water levels in the Rincón study area are mainly affected by wind and semi-diurnal tidal fluctuations of the Mona Passage connecting the Atlantic Ocean and Caribbean Sea basins. Tidal datums near the Rincón study area were gathered using NOAA's Mayagüez, Puerto Rico Station 9759394 shown in Figure A-33. This NOAA gauge presently contains astronomical tide data since March 2008. Table A-3 shows the elevations from that gauge, which are referred to in PRVD02, from the tidal epoch period spanning from 1983 to 2001. The findings are based on a 2-year analysis period ranging from May 2015 to April 2017 and have a mean tidal range of 1.04 feet. The Puerto Rico Coastal Study used these elevations for the Rincón modeling and alternative design activities. While the San Juan study area contains the same datum elevations for MSL and PRVD02, Rincón's local water levels average slightly higher than the static PRVD02 elevation. Thus, MSL and PRVD02 are not interchangeable in this location.

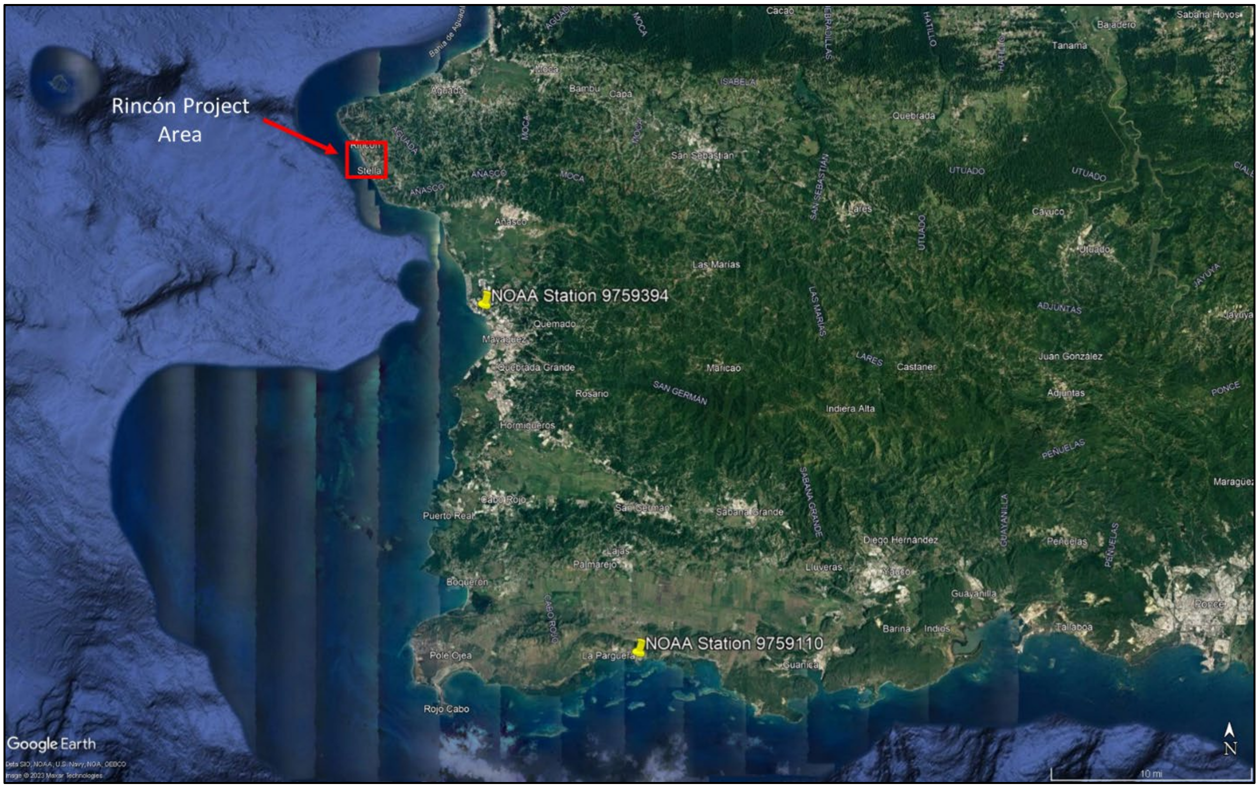


**Figure A-33. NOAA Tide Stations with Long-Term Records in the Vicinity of Rincón, Puerto Rico**

**Table A-3. Rincón Tidal Datums (NOAA Station 9759394)**

| Location: 18° 13.1' N, 67° 9.7' W<br>Analysis Period: May 2015 - Apr. 2017 | |
|---|---|
| **Datum** | **Elevation (feet PRVD02)** |
| Mean Higher-High Water | 0.88 |
| Mean High Water | 0.67 |
| Mean Sea Level | 0.14 |
| Puerto Rico Vertical Datum of 2002 | 0.00 |
| Mean Low Water | -0.37 |
| Mean Lower-Low Water | -0.49 |

### *2.1.2 Wind*

The earth and its atmosphere are a continually changing dynamic system. Earth's air, for instance, is constantly driven by the globe's rotation on its axis, its revolution around the sun, and the transfer of energy from the sun. Solar energy heats the earth unevenly due to the planet's motions. This non-uniform energy distribution induces constantly shifting circulation patterns, which manifest themselves in the form of winds (Bredesen, 2015). The energy transfer process continues into the earth's surface, where sporadic heating from the sun assists the macro-scale water movements creating ocean currents. Wind transfers energy into the water's surface due to friction and pressure gradients, building waves and inducing surface currents. Winds can contribute to storm surge and the generation of waves, which are both important contributors to infrastructure damage throughout the study area.

The Commonwealth of Puerto Rico lies within the tropical trade wind zone resulting in moderate winds from a prevailing easterly direction all year long. Increased north-northeast winds during the fall, winter, and spring seasons primarily occur from nor'easters in the mid- to northern-Atlantic Basin. Extreme conditions from tropical systems generally impact the island in the summer and fall months. Wind data around the island are available from sources such as USACE's Wave Information Studies (WIS) and NOAA's various platforms for coastal and climatological data.

The WIS database is a valuable resource for general wind information (Section 4.2.1 details other sources for modeling-specific wind data input). WIS is a wind and wave hindcast database for various stations located along the U.S. Atlantic, Gulf of Mexico, and Caribbean coastlines (USACE, 2022a). Wind forcing in WIS applies 10-mile (i.e., 33-foot) wind fields from the National Centers for Environmental Predictions and National Center for Atmospheric Research Reanalysis (Kalnay et al., 1996). The reanalyzed winds are enhanced for significant storm events using statistical downscaling, in-situ and satellite wind data assimilation, and dedicated analysis of significant tropical and nor'easter storms systems. Available data for this study include offshore save point stations around Puerto Rico that contain hindcast time series of wind speed, wind direction, wave height, wave period, and wave direction in 1-hour intervals for a 40-year period that spans from January 1980 to January 2020 (Figure A-34).

NOAA's Integrated Ocean Observing System (IOOS) is also a useful resource for wind data around Puerto Rico. The IOOS produces and compiles high-quality coastal, ocean, and lake data across 11 regions spanning the U.S. Pacific, Atlantic, Great Lakes, and Caribbean coasts. Compiled data from sources such as satellites, ocean buoys, and pressure gauges are displayed in an integrated view for each region. The Caribbean Integrated Coastal Ocean Observing System (CARICOOS) database hosts the IOOS Caribbean Region developed for Puerto Rico and the Virgin Islands that brings together coastal ocean data including wind, waves, tides, and ocean currents. Notable CARICOOS data around Puerto Rico include NOAA's National Data Buoy Center's (NDBC) stations near San Juan and Rincón. Figure A-35 shows the CARICOOS stations closest to Puerto Rico.

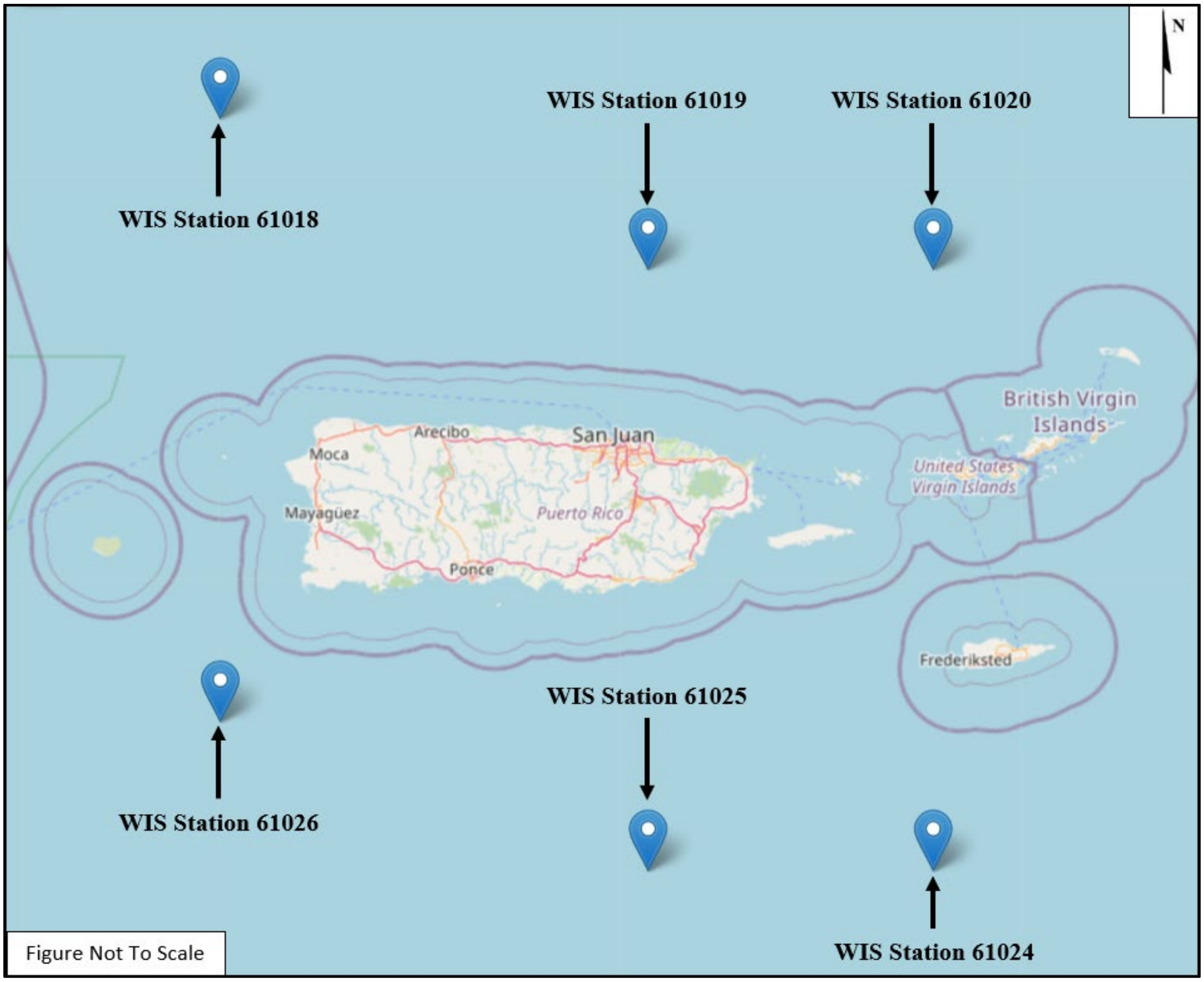


**Figure A-34. WIS Stations around Puerto Rico**


**Figure A-35. CARICOOS Stations around Puerto Rico**

#### 2.1.2.1 Winds in San Juan

While NDBC Station 41053, which lies just off the San Juan coastline (18° 28.4' N, 66° 5.9' W), contains wind data from 2010 to 2021, WIS Station 61019 (approximately 37.0 miles north of San Juan at 19° 0.0' N, 66° 0.0' W) is the closest station to the San Juan study area with somewhat of a long-term record (40 years versus 12 years). Figure A-36 shows both stations, but USACE primarily used the WIS station to assess the general wind climate in San Juan due to its longer record of data compared to the NDBC gauge. Table A-4, Table A-5, and Figure A-37 show the dominant easterly wind direction that accounts for roughly 94.0 percent of the recorded winds in the area. Predominant winds are also the strongest recorded winds on average, where highlighted cells represent the maximum average winds from the east to northeast directional bands during the nor'easter storm season at 16.7 miles per hour (mph) from December to January. These data show the prevalence of tropical trade winds in San Juan but do not fully detail wind impacts in the area. Tropical wind forcing is much less frequent but much more intense. In the matter of hours, hurricane wind fields can batter San Juan with wind gusts over 150 mph (i.e., Hurricane Irma and Hurricane Maria in 2017).

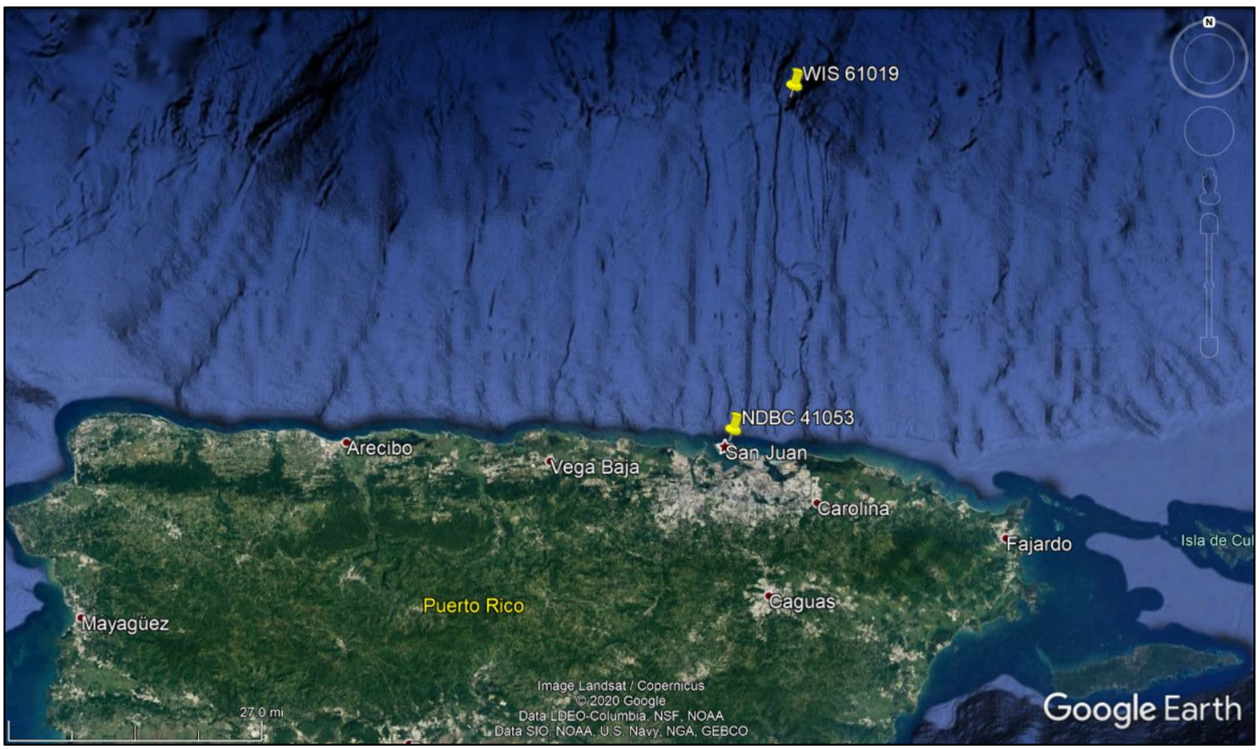


**Figure A-36. NDBC and WIS Stations near San Juan, Puerto Rico**

**Table A-4. General San Juan Wind Climate**

| Wind Direction (from) | WIS Station 61019 (1980-2020) | |
|---|---|---|
| | Percent Occurrence (%) | Average Wind Speed (mph) |
| North | 1.7 | 13.0 |
| Northeast | 13.8 | **16.4** |
| East | **66.6** | 15.9 |
| Southeast | 13.6 | 12.2 |
| South | 2.5 | 10.8 |
| Southwest | 0.7 | 10.2 |
| West | 0.5 | 10.6 |
| Northwest | 0.6 | 11.5 |

**Table A-5. Seasonal San Juan Wind Climate by Month**

| Month | WIS Station 61019 (1980-2020) | |
|---|---|---|
| | Average Wind Speed (mph) | Wind Direction (from) |
| January | **16.7** | East |
| February | 16.3 | East |
| March | 15.1 | East |
| April | 14.1 | East |
| May | 13.7 | East |
| June | 15.0 | East |
| July | 16.6 | East |
| August | 15.6 | East |
| September | 13.7 | East |
| October | 13.2 | East |
| November | 15.4 | East |
| December | **16.7** | East |

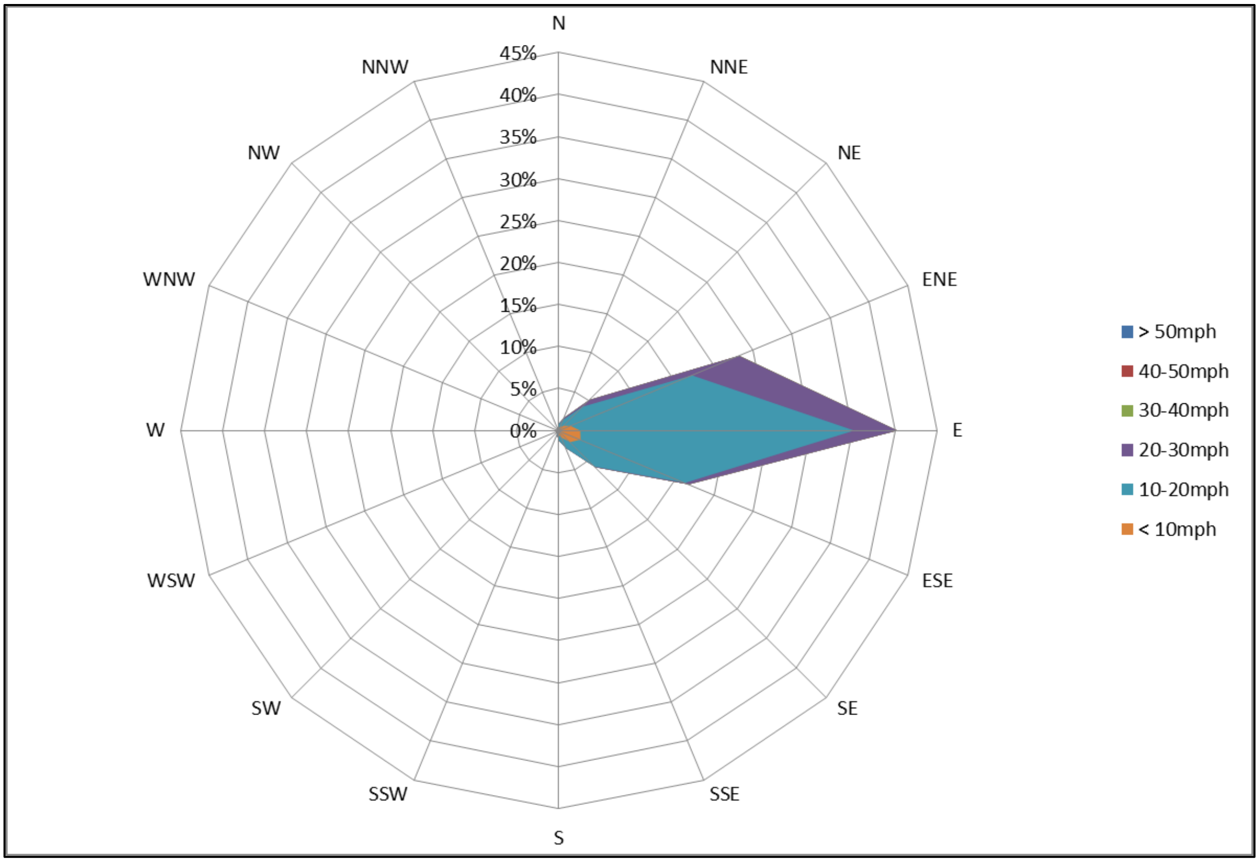


**Figure A-37. General San Juan Wind Climate (WIS Station 61019)**

2.1.2.2 Winds in Rincón

The three wind stations closest to the Rincón study area are WIS 61018, WIS 61026, and NDBC PTRP4 (Figure A-38). WIS Station 61018 (19° 30.0' N, 67° 30.0' W) lies roughly 81.0 miles NNW of the Rincón study area in the Atlantic Ocean, and WIS Station 61026 (17° 30.0' N, 67° 30.0' W) lies approximately 60.0 miles SSW of Rincón in the Caribbean Sea. While these two stations contain 40 years of hindcast wind data, they are too far from the study area to be considered within the local wind regimen. However, NDBC PTRP4 is an inland wind gauge that includes a 10-year period of record from 2012 to 2021 and is located 1.7 miles NE of the Rincón study area at 18° 22.0' N, 67° 15.1' W. Table A-6 and Figure A-39 show that the prevailing winds (like in San Juan) are from the eastern quadrant, where 79.2 percent of the wind records come from the NE to SE directions. Tropical systems, as previously mentioned, impact the area on a less frequent basis; thus, extreme wind conditions are not represented in the average wind data shown below, and hurricane winds can exceed 150 mph (i.e., Hurricane Maria).

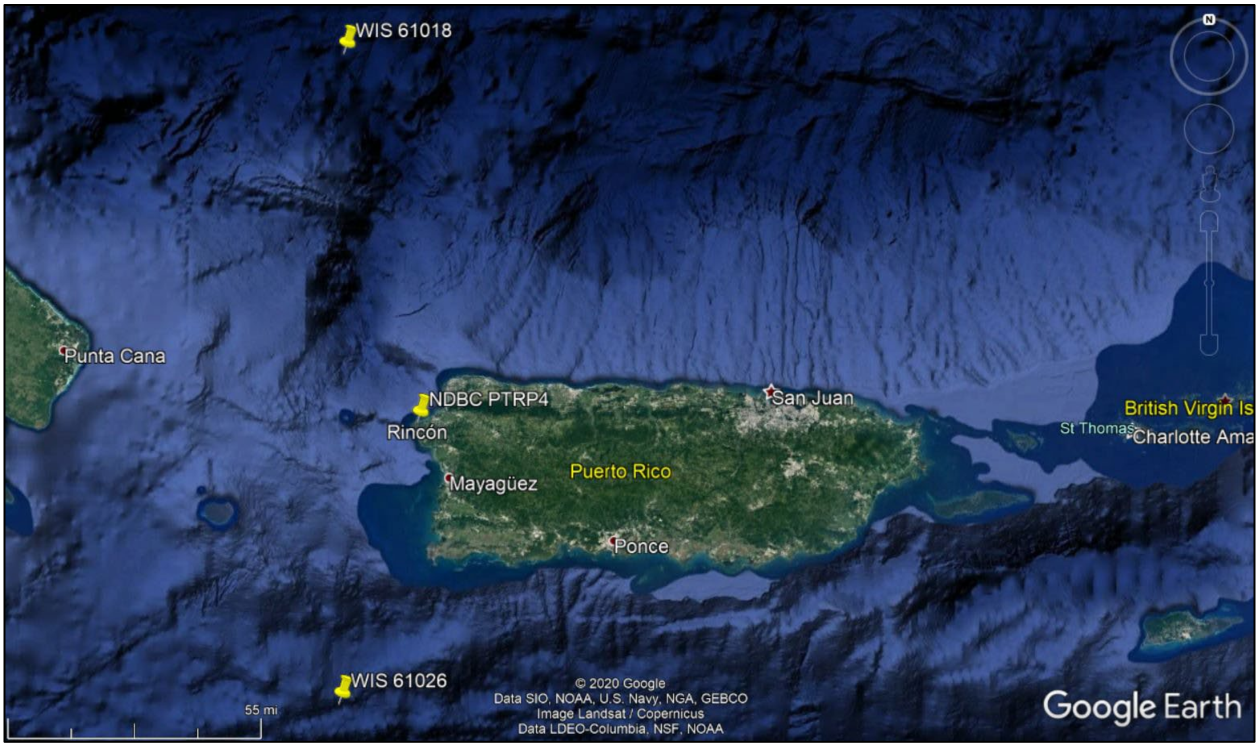


**Figure A-38. NDBC and WIS Stations near Rincón, Puerto Rico**

**Table A-6. General Rincón Wind Climate**

| Wind Direction (from) | NDBC Station PTRP4 (2012-2021) | |
|---|---|---|
| | Percent Occurrence (%) | Average Wind Speed (mph) |
| North | 7.7 | 7.4 |
| Northeast | 21.5 | **7.5** |
| East | **44.6** | 5.4 |
| Southeast | 13.1 | 4.0 |
| South | 4.4 | 5.2 |
| Southwest | 2.0 | 4.3 |
| West | 2.3 | 3.0 |
| Northwest | 4.4 | 3.6 |

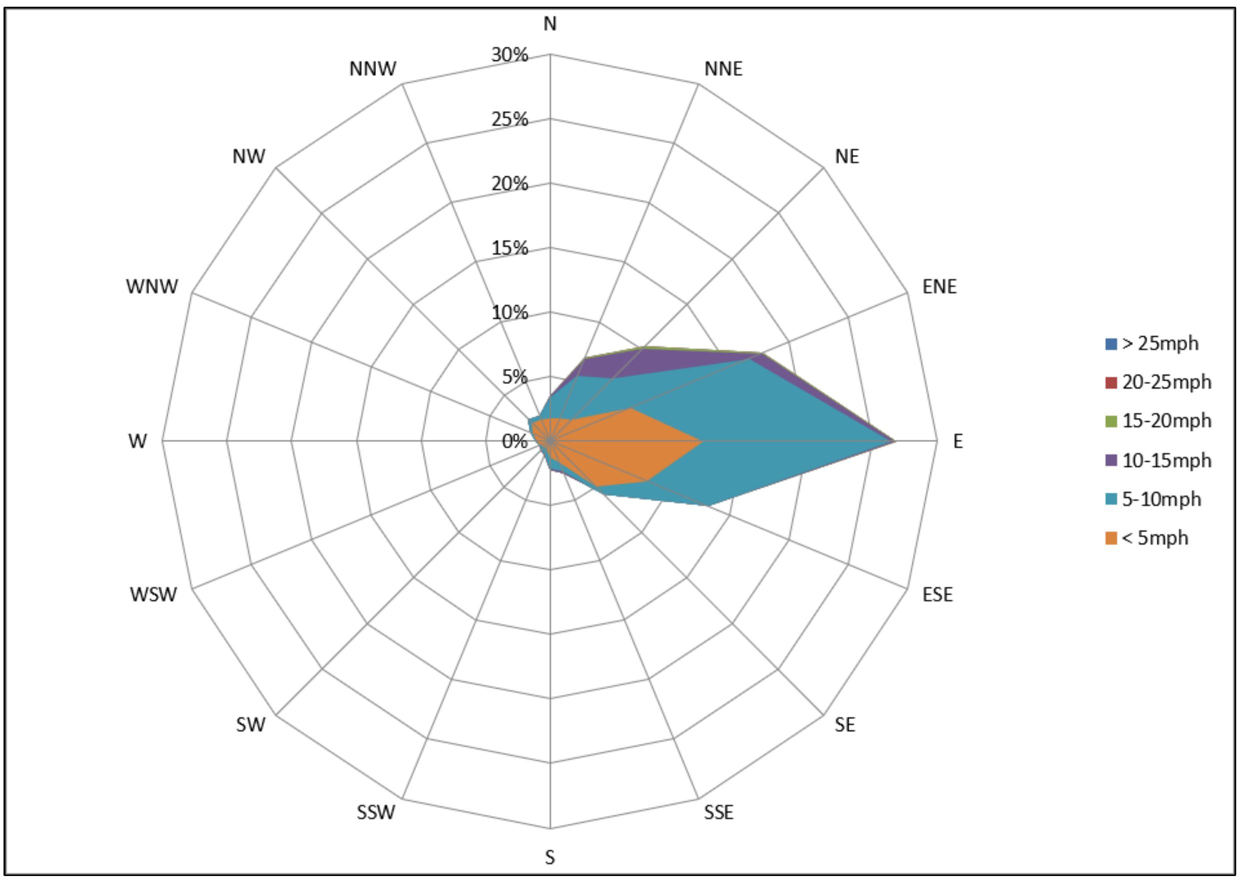


**Figure A-39. General Rincón Wind Climate (NDBC Station PTRP4)**

### *2.1.3 Incident Waves*

Although individual wave events are considered short-term processes, coastlines nearly always endure the presence of waves due to the vastness of ocean surface area and the non-stop movement of the earth's atmosphere. Waves can be generated from thousands of miles away or immediately adjacent a shoreline's location. Wind that imparts energy to the ocean's surface far from a study site can drive a wave train over a long fetch, generally resulting in higher periods and wave heights. Local, small-fetch wind-driven waves can yield high-frequency wave attack problems to local coastline infrastructure; and while waves are generated close to and far from a study site, they are usually the prime drivers for coastline damages. This section discusses the general wave climate in San Juan and Rincón, but Section 4.2.1 discusses the specific wave characteristics used in modeling efforts in more detail.

USACE, SAJ obtained wave data around the island and near the two focus areas of San Juan and Rincón from similar gauges or hindcast databases as detailed in the general wind climate section (Section 2.1.2). Six WIS stations around the island contain wave height, wave period, and wave direction data in 1-hour intervals for the 40-year period of record (1980-2020) as shown in Figure A-34. NOAA's CARICOOS data portal compiles notable wave data stations around Puerto Rico, including the NDBC stations near San Juan and Rincón (Figure A-35).

#### 2.1.3.1 Waves in San Juan

The wave stations that are closest to the San Juan study area are the same gauges as detailed in Section 2.1.2.1 and shown in Figure A-36 (WIS Station 61019 and NDBC Station 41053). WIS Station 61019 provides 40 years of offshore, deep-water wave characteristics from 1980 to 2020, and NDBC Station 41053 lies just off the San Juan coastline with recorded data in shallower water from 2010 to 2021. Since the WIS station contains a longer data period, these data are used to describe San Juan's wave forcing, but the NDBC station is still important as it helped derive the nor'easter storm suite for modeling activities (see Section 4.2.1).

Since most waves are generated by wind, general wave conditions in both study sites (San Juan and Rincón) follow similar trends as the wind conditions presented in Section 2.1.2. San Juan is largely exposed to smaller, moderate-period waves from the east-northeast in the warmer months (April through October), and this area experiences larger, longer-period waves from the east-northeast in the cooler months (November through March). Table A-7 and Table A-8 detail this information where cells highlighted yellow represent the maximum values in each column, and cells with italicized blue text in Table A-8 signify the maximum percent occurrence by month for each 1-second period bin. The aggregate percent occurrence by directional band (Table A-7) shows the dominant eastern quadrants comprise roughly 94.1 percent of all wave data for this WIS station (predominant local easterly wind-driven waves), and the larger, less frequent waves come from the north (likely longer fetch waves from northern latitude nor'easter systems). Table A-8 confirms this trend. Blue italicized columns show the calmer summer months of June through August dominate the shorter period bins from 4.0 to 9.9 seconds, and the nor'easter months of January through March dominate the longer period bins from 10.0 to 12.0+ seconds. Further, the bottom-line wave heights in this region range from an average of 5.3 feet in May to 7.8 feet in January. Figure A-40 displays the general wave climate in San Juan, with the wave direction generally ranging from north north-east to east.

**Table A-7. General Ocean Park Wave Climate by Direction**

| Wave Direction (from) | WIS Station 61019 (1980-2020) | |
|---|---|---|
| | Percentage Occurrence (%) | Average Wave Height (feet) |
| North | 5.7 | 7.0 |
| Northeast | 30.1 | 6.5 |
| East | **63.7** | 6.2 |
| Southeast | 0.2 | 5.9 |
| South | 0.0 | - |
| Southwest | 0.0 | - |
| West | 0.0 | - |
| Northwest | 0.2 | **7.8** |

**Table A-8. Seasonal Ocean Park Wave Climate by Month**

| Wave Period (Seconds) | WIS Station 61019 (1980-2020) Percent Occurrence (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. |
| < 4.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 4.0 - 4.9 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 | ***0.2*** | 0.0 | 0.0 | 0.0 | 0.0 |
| 5.0 - 5.9 | 0.2 | 0.0 | 0.2 | 0.3 | 0.3 | 0.5 | 0.2 | ***0.6*** | 0.3 | 0.3 | 0.1 | 0.1 |
| 6.0 - 6.9 | 0.6 | 1.0 | 0.8 | 2.1 | 2.6 | 2.9 | 2.1 | ***6.2*** | 5.6 | 5.1 | 1.5 | 0.8 |
| 7.0 - 7.9 | 2.7 | 2.5 | 5.4 | 7.0 | 10.3 | 11.5 | 14.3 | ***21.1*** | 17.9 | 12.3 | 6.7 | 6.2 |
| 8.0 - 8.9 | 13.4 | 13.6 | 16.6 | 23.6 | **35.2** | **44.5** | **45.4** | **43.0** | **30.3** | **29.4** | 23.1 | 14.9 |
| 9.0 - 9.9 | **32.2** | **31.5** | **28.9** | **32.0** | 32.8 | ***35.8*** | 35.2 | 21.1 | 20.0 | 23.2 | **28.3** | **29.1** |
| 10.0 - 10.9 | ***28.8*** | 26.4 | 21.3 | 14.8 | 9.7 | 3.5 | 2.5 | 3.5 | 11.1 | 10.9 | 17.3 | 19.9 |
| 11.0 - 11.9 | 12.2 | ***13.0*** | 10.0 | 8.3 | 5.2 | 0.7 | 0.1 | 2.1 | 6.1 | 8.7 | 10.5 | 12.9 |
| ≥ 12.0 | 9.9 | 12.1 | ***16.8*** | 12.0 | 4.0 | 0.6 | 0.2 | 2.3 | 8.6 | 10.2 | 12.5 | 16.1 |
| **Avg. Wave Height** | **WIS Station 61019 (1980-2020) Average Wave Height by Month** | | | | | | | | | | | |
| | **Jan.** | **Feb.** | **Mar.** | **Apr.** | **May** | **June** | **July** | **Aug.** | **Sep.** | **Oct.** | **Nov.** | **Dec.** |
| **feet (from)** | **7.8 (E)** | 7.5 (E) | 6.8 (E) | 6.0 (E) | 5.3 (E) | 5.4 (E) | 6.1 (E) | 5.6 (E) | 5.4 (E) | 5.6 (NE) | 7.0 (NE) | 7.7 (NE) |

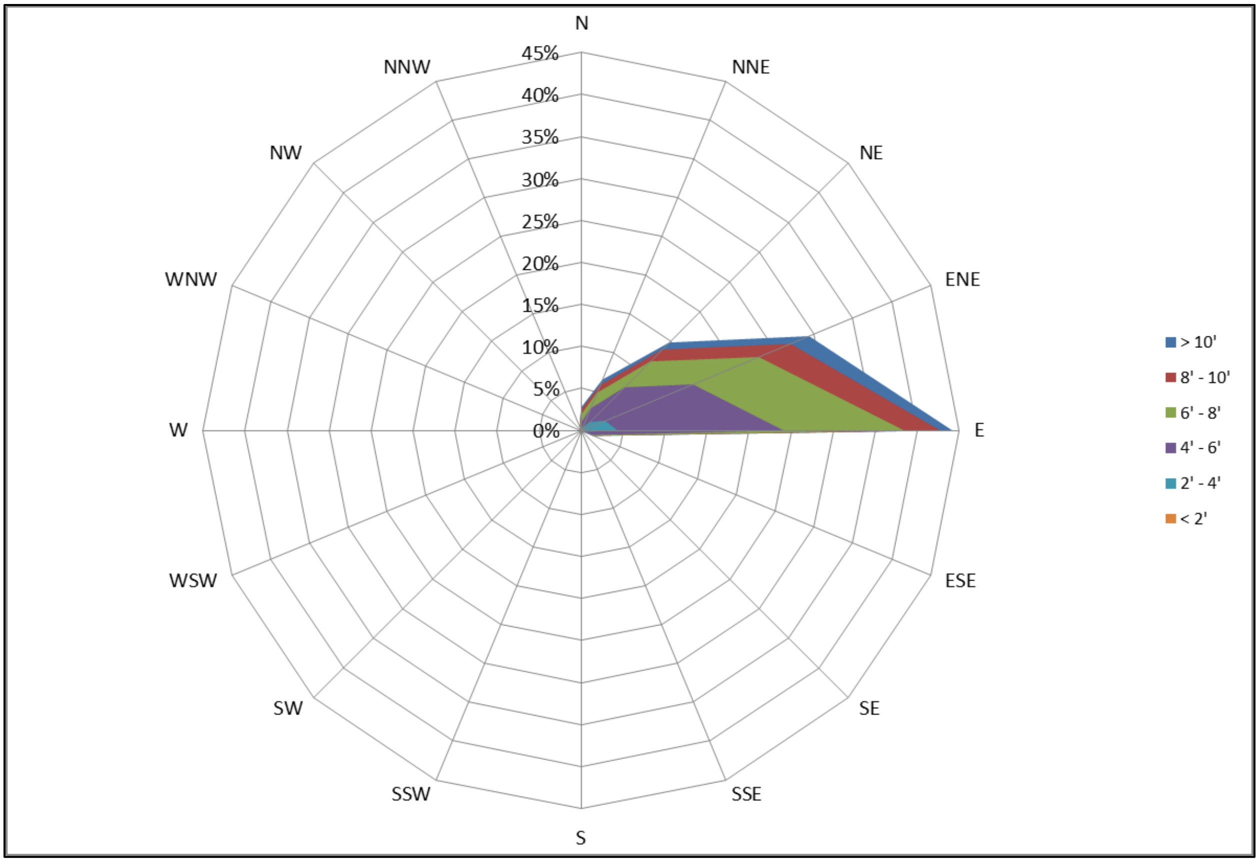


**Figure A-40. General San Juan Wave Climate**
**(WIS Station 61019)**

##### *2.1.3.1.1 <u>San Juan's Fringing Reef</u>*

These data provide a good indication of incoming waves that affect the coastal areas of San Juan, but they may not tell the full story of wave impacts to the focused area of interest. The fringing reef discussed previously in Section 1.3.1 plays a major role in dissipating incoming wave energy. Shallow areas in the fringing reef induce wave breaking and reduce wave energy that reaches the coastline. However, gaps, or sections of deep water between shallow reef heads, in the reef can alternatively act as "funnels" that may focus wave energy along certain portions of the coastline. Malej et al. (2020) simulated raw wave data from data collected by the Caribbean Oceanography Group as part of the wave modeling for the Condado Reef Project (Torruella, 2015). Physical acoustic Doppler profilers (ADPs) made by Nortek and labeled "AWAC", in Figure A-41, collected these wave data. This figure shows a single wave event from the FUNWAVE validation model run, where the heat map displays enhanced wave energy hitting shorelines in lee of the deeper reef areas and reduced wave energy for shorelines in lee of shallower reef areas.

The most notable gap is in western/central Ocean Park. Two or three dimensional (2D or 3D) hydrodynamic and wave modeling would be needed to fully understand the wave environment (and how waves effect nearshore circulation) landward of the fringing reef across the entire study area, and while this figure is only a single event (i.e., does not represent all wave events), it still shows the relative impact the fringing reef depths can have on this stretch of coast. Notably, USACE also used the AWAC gauges shown in Figure A-41 to attenuate offshore NDBC data needed for Beach-*fx* modeling efforts on this Puerto Rico Coastal Study (further discussed in Section 4.2.1.2.1).

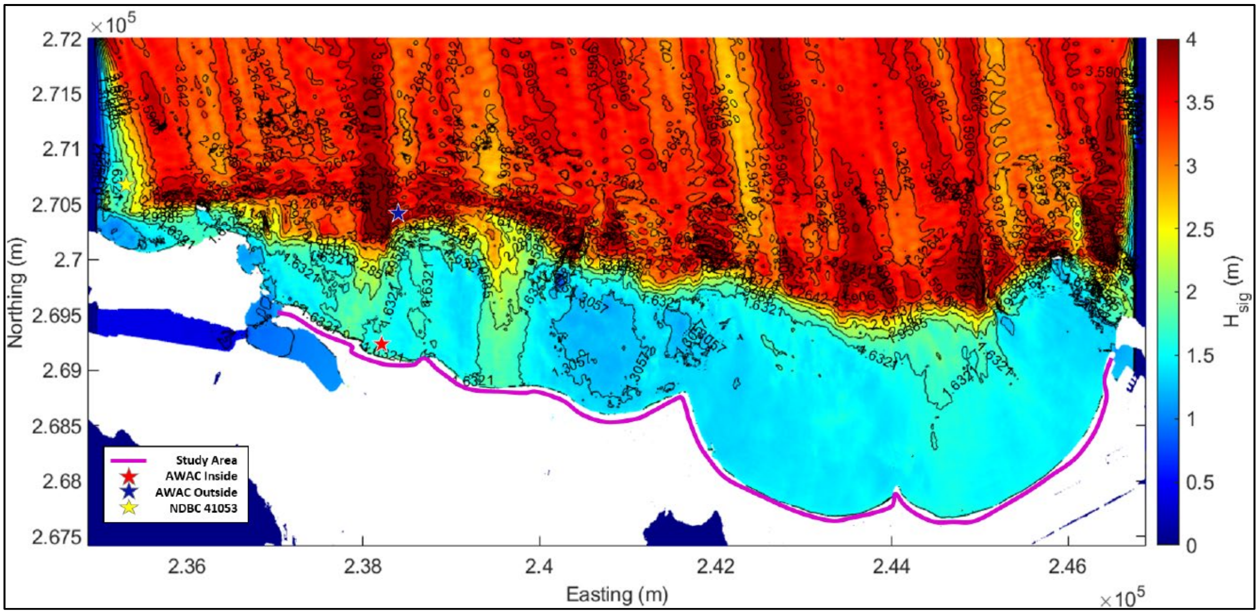


**Figure A-41. A 2015 Swell Event's Significant Wave Height Heat Map in San Juan (Malej, et al., 2020)**

### 2.1.3.2 Waves in Rincón

Rincón is largely exposed to smaller, moderate-period waves from the northern directional quadrants in the warmer months (April through October), and this area experiences larger, longer-period waves from the north in the cooler months (November through March). Table A-9 and Table A-10 detail this information, where these data for Rincón were sampled from NDBC Station 41115, located approximately 3.5 miles NW of the Rincón study area at 18° 22.6' N, 67° 16.8' W. Cells highlighted yellow represent the maximum values in each column and cells with italicized blue text in Table A-10 signify the maximum percent occurrence by month for each 1-second period bin. The aggregate percent occurrence by directional band (Table A-9) shows the dominant northern quadrants comprise roughly 95.5 percent of all wave data for this NDBC station. Table A-10 shows larger, longer-period waves (9.0+ seconds) are present in nor'easter season from November through March (blue italicized columns), and calmer summer months of June through August dominate the shorter period bins under 9.0 seconds. Further, the bottom-line wave heights in this region range from an average of 1.9 feet in June to 4.1 feet in March. Figure A-42 displays the general wave climate in Rincón, with the wave direction generally ranging from north north-west to the north north-east.

**Table A-9. Rincón's Average Wave Height by Direction**

| Wave Direction (from) | NDBC Station 41115 (2011-2021) | |
|---|---|---|
| | Percentage Occurrence (%) | Average Wave Height (feet) |
| North | **76.1** | **3.3** |
| Northeast | 14.8 | 2.6 |
| East | 0.1 | 2.0 |
| Southeast | 0.0 | 2.0 |
| South | 0.4 | 2.3 |
| Southwest | 2.2 | 2.1 |
| West | 1.8 | 2.0 |
| Northwest | 4.6 | 2.9 |

**Table A-10. Rincón's General Wave Period Percent Occurrence (NDBC Gauge 41115)**

| Wave Period (Seconds) | NDBC Station 41115 (2011-2021) Percent Occurrence (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. |
| < 4.0 | 0.3 | 0.4 | 0.4 | 1.6 | 1.7 | 5.9 | *7.6* | 6.5 | 3.0 | 0.4 | 0.1 | 0.4 |
| 4.0 - 4.9 | 0.2 | 1.1 | 0.4 | 1.2 | 2.2 | 4.6 | *8.9* | 7.6 | 3.3 | 0.8 | 0.1 | 0.3 |
| 5.0 - 5.9 | 2.1 | 3.1 | 1.9 | 3.0 | 11.4 | 15.6 | **30.2** | 32.1 | 10.6 | 5.3 | 2.3 | 2.7 |
| 6.0 - 6.9 | 6.2 | 6.6 | 7.0 | 8.1 | **15.8** | **21.9** | *29.3* | 23.3 | 8.7 | 5.1 | 3.5 | 5.7 |
| 7.0 - 7.9 | 12.0 | 9.9 | 9.3 | 13.4 | 14.4 | *15.4* | 13.7 | 9.9 | 9.8 | 8.6 | 7.6 | 7.6 |
| 8.0 - 8.9 | 8.6 | 6.8 | 7.6 | *11.7* | 6.6 | 5.8 | 2.9 | 2.6 | 8.8 | 8.5 | 10.7 | 6.6 |
| 9.0 - 9.9 | **22.4** | 20.4 | **24.1** | **21.2** | **15.8** | 10.9 | 3.7 | 6.9 | **18.9** | **21.5** | **31.2** | 33.4 |
| 10.0 - 10.9 | 11.5 | 10.6 | 11.3 | 8.3 | 8.1 | 3.9 | 1.3 | 3.2 | 8.3 | 11.5 | 11.2 | *11.6* |
| 11.0 - 11.9 | 19.7 | 16.8 | 16.6 | 11.4 | 12.5 | 8.1 | 1.3 | 5.5 | 16.1 | *19.8* | 14.4 | 13.9 |
| ≥ 12.0 | 17.0 | 24.5 | 21.5 | 20.1 | 11.5 | 7.9 | 1.1 | 2.4 | 12.5 | 18.7 | 18.9 | 17.8 |
| **Avg. Wave Height** | **NDBC Station 41115 (2011-2021) Average Wave Height by Month** | | | | | | | | | | | |
| | **Jan.** | **Feb.** | **Mar.** | **Apr.** | **May** | **June** | **July** | **Aug.** | **Sep.** | **Oct.** | **Nov.** | **Dec.** |
| **feet (from)** | **3.9 (N)** | 4.0 (N) | **4.1 (N)** | 3.2 (N) | 2.5 (N) | 1.9 (N) | 2.1 (N) | 2.1 (N) | 2.7 (N) | 2.1 (N) | 4.0 (N) | 4.0 (N) |

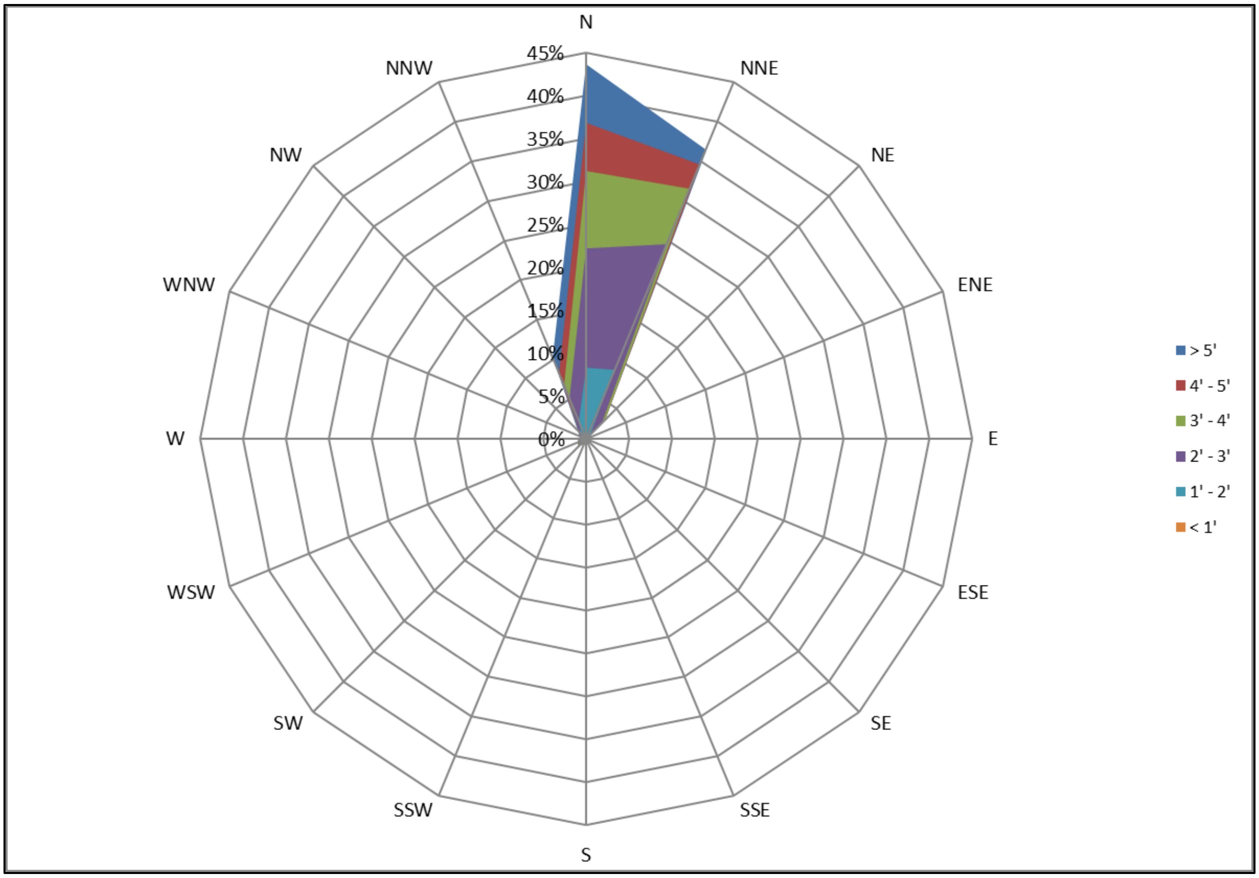


**Figure A-42. General Rincón Wave Climate (NDBC Station 41115)**

*2.1.3.2.1 Wave Refraction North of the Rincón Study Area*

These data from Section 2.1.3.2 provide a good indication of the general wave climate just north of Rincón, but the data may not tell the full story of wave impacts to the focused area of interest. The natural point feature just north of the study area plays a major role in refracting northern wave trains and dissipating incoming wave energy. Malej, et al. (2020) conducted wave simulations in the FUNWAVE model, like the simulations run in San Juan (Section 2.1.3.1.1). Figure A-43 shows a single wave event from FUNWAVE in Rincón where natural wave refraction and dampening is noted by diminishing “ripples” in the free-surface time snapshot (color contour shown has units of meters). Figure A-44 similarly shows diminishing wave energy as the northerly wave event progresses to the study area coastline. While this figure is only a single event (i.e., does not represent all wave events), it still shows the relative impact the natural headland can have on this stretch of coast, especially since roughly 95.5 percent of all recorded wave events from 2011 to 2021 came from the north (Section 2.1.3.2).

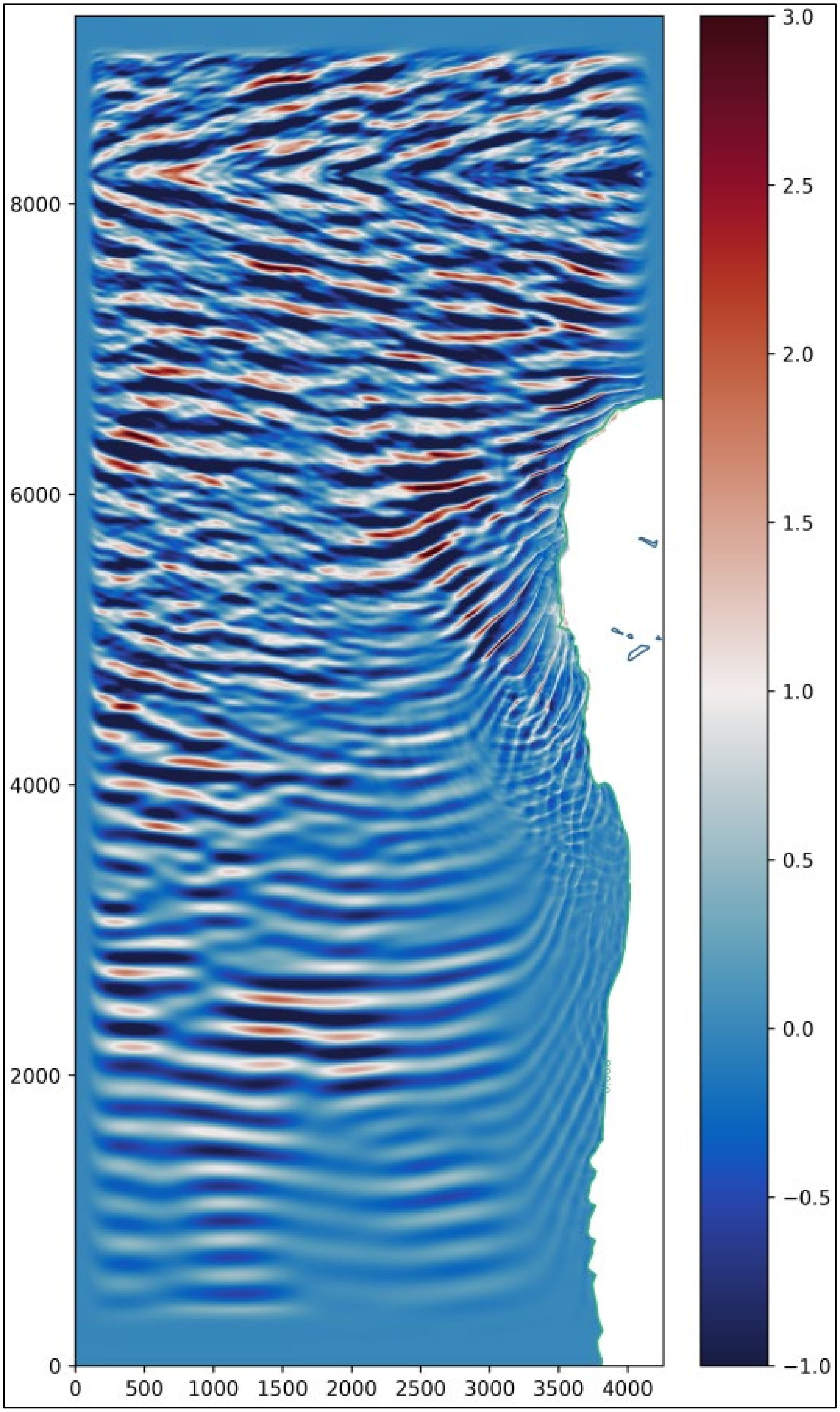


**Figure A-43. Free-Surface Snapshot for a FUNWAVE Event (meters) near Rincón (Malej, et al., 2020)**

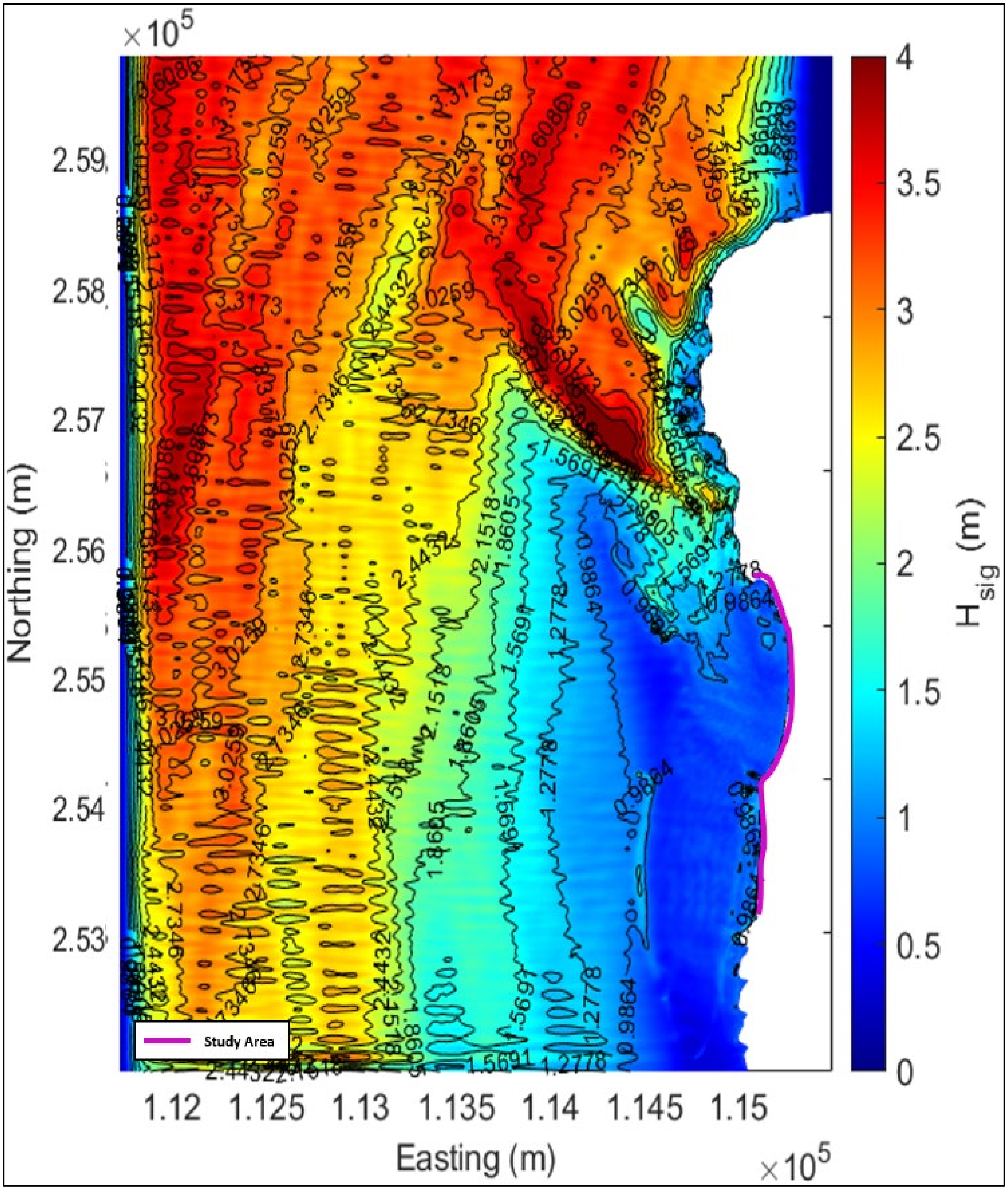


**Figure A-44. A 2015 Swell Event's Significant Wave Height Heat Map near Rincón (Malej, et al., 2020)**

#### 2.1.3.3 Infra-gravity Waves

A phenomenon that is not generally discussed or analyzed in CSRM studies but could greatly influence overall damages to CSRM solutions in areas like San Juan, Puerto Rico is the presence of infra-gravity (IG) waves. IG waves are low frequency, long period (i.e., on the order of 30 seconds to 10 minutes) waves that are generated when short(er) period waves (i.e., under 20 seconds) with varying wave lengths and frequencies are superposed to create wave energy at IG frequencies. IG waves, created from these non-linear wave-wave interactions, can occur in deep or shallow water, and focus on IG waves is generally within harbors where IG frequencies can cause resonance problems for harbor structures and vessel navigation. However, studies such as Dean and Dalrymple (2002; p. 380) indicate that substantial IG wave activity was measured before, during, and after significant hurricane events in the nearshore zone. Further, quasi-closed-cell beaches, such as the San Juan study area beaches, could act as small-scale embayment nearshore features that could experience similar resonance problems as harbors do.

Figure A-45 (Brown, 2013) shows an example of IG wave creation. The top plot represents two wave trains in the same location. When the two wave trains are misaligned, they act to dampen each other; conversely, when the two wave trains are in sync, they enhance the grouped amplitude. The bottom plot represents the grouped wave train and resulting IG wave.

An IG wave propagating to a coastline dissipates differently over mild or steep slopes in the nearshore zone, and Battjes et al. (2004) and de Bakker et al. (2016) note that the bound IG wave, such as the one shown in Figure A-45, transfers greatest energy at the shoreline of mildly sloping beaches versus steep-sloped shorelines. While the fringing reef discussed in Section 2.1.3.1.1 will help attenuate IG wave energy at greater rates than locations without a steep-sloped outer reef or bar, gaps in the fringing reef may act as a funnel for these waves to have a greater impact in shoreline areas directly in lee of the reef gaps. Further, IG waves in the nearshore zone can reflect off beaches or structures and transform into leaky waves or edge waves depending on bathymetry and incidental propagation direction (Herbers, et al., 1995). Leaky waves are waves reflected seaward, and edge waves are waves trapped, standing waves in the cross-shore direction (Bryan, et al., 1998). Given the complex hydrodynamic environment present in both study areas, further studies in San Juan and Rincón, Puerto Rico should include IG wave assessment to ensure a complete CSRM solution that minimizes adverse impacts to this important phenomenon (i.e., in the PED phase for this project).

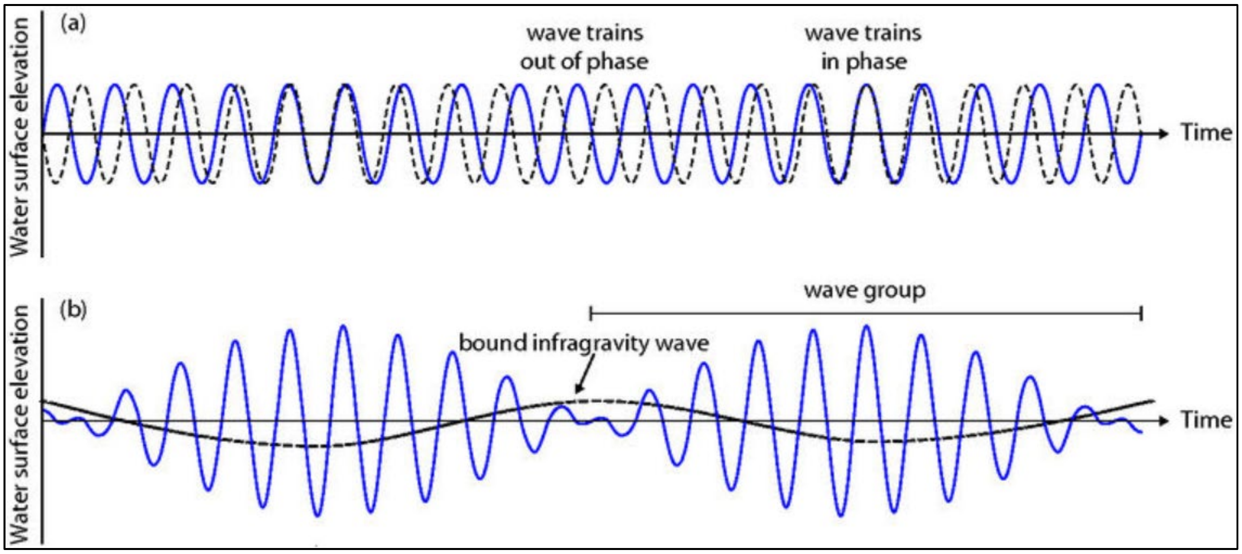


**Figure A-45. IG Wave Creation Example**
**(Brown, 2013)**

### *2.1.4 Storm Surge*

Storm surge is the rise of the ocean's surface above typical astronomical tide elevations that results from storm systems. Surge occurs from atmospheric pressure gradients, wind-to-ocean surface stresses, the Coriolis Force, and static wave setup (Dean and Dalrymple, 2002). Surge is generally greatest during extreme tropical systems, where water level superelevation from surge exacerbates inundation along ocean coastlines and propagate through inlets, intensifying inland flooding from bay-side coastlines. Total water level elevation that includes storm surge is critical to understanding total damage potential in coastal areas, so the additional water level experienced in a study area from storm surge needs to be included in CSRM modeling applications.

Predicting or estimating storm surge in Puerto Rico is somewhat difficult owing to the lack of long-term water level records along with site-specific evidence or recordings of surge levels for extreme events without other water level input like tide levels and dynamic wave effects. Further, dynamic wave-wave interactions in the nearshore zone of hydrodynamically complex areas like San Juan and Rincón may introduce uncertainty in water levels that relate to only storm surge. Thus, these data are sometimes referred to as SWEs. Reniel-Calzada and Mercado-Irizarry (2020) noted this data deficiency in the recent Puerto Rico Storm Surge Atlas update, where wave setup (rather important in places like Puerto Rico) was included in the latest FEMA FIS (FEMA, 2012). Data collected from the same NOAA stations detailed in Section 2.1.1 and information from FEMA (2012) and Reniel-Calzada and Mercado-Irizarry (2020) yielded the SWEs listed in Table A-11. This table relates a particular event's SWE at the study areas to an annual exceedance probability (AEP), or how often a SWE will exceed a given threshold on an annual basis. For example, a surge event that exceeds 1.8 feet PRVD02 in Ocean Park has historically occurred once in a 5-year span (or an AEP of 20 percent).

The NOAA gauges from where USACE, SAJ collected these data are not directly in front of the study areas, so they will include uncertainty. USACE, SAJ gathered the SWEs listed for San Juan from NOAA tide station 9755371 (San Juan, La Puntilla) in the San Juan Bay, which may not include static wave setup since this station is on the bay side of the study area (as shown in Figure A-32). Thus, the SWE is likely higher along the open-ocean coastline in San Juan than the 20 percent to 1 percent SWE range of 1.8 to 2.5 feet PRVD02 as reported below. Further, USACE, SAJ gathered SWEs in Rincón from NOAA Station 9759110 (Magueyes Island), which is south of the study area (shown in Figure A-33) and protected from northerly surge events (most events impacting the Rincón study area). USACE, SAJ selected NOAA Station 9579110 since it is the only NOAA gauge on the west coast of Puerto Rico that contains enough data to support NOAA AEP events. Thus, the SWE is likely higher at the Rincón study area than the 20 percent to 1 percent SWE range of 1.1 to 2.2 feet PRVD02 as reported below. Hence, storm surge in modeling-specific storm input were defined by the recently available Coastal Hazards System (CHS) stations closer to the two study areas (further detailed in Section 4.2.1).

**Table A-11. Approximated SWEs for San Juan and Rincón**

| Annual Exceedance Probability (%) | Associated Return Interval ($yrs^{-1}$) | San Juan's Approx. SWE (ft PRVD02)[1] | Rincón's Approx. SWE (ft PRVD02)[2] |
|---|---|---|---|
| 20 | 5 | 1.8 | 1.1 |
| 10 | 10 | 1.9 | 1.3 |
| 2 | 50 | 2.3 | 1.9 |
| 1 | 100 | 2.5 | 2.2 |

1: From NOAA Station 9755371 reported with surge and tides
2: From NOAA Station 9759110 reported with surge and tides

## 2.2 Long-Term Coastal Processes

The three predominant long-term coastal processes considered in the Puerto Rico Coastal Study are seasonal circulation patterns (most notable for the San Juan study area), relative SLC, and decadal shoreline evolution. Seasonal circulation patterns are the shifting of sediment between seasonally dominated climatological events. Relative SLC forms a backdrop for coastline evolution and is directly correlated to long-term geological and climatological processes such as land subsidence and global temperature change (Bredesen, 2015). Accreting or eroding shorelines not only play an important role in the performance of manmade coastal structures, but they can also influence natural coastline features (Dean and Dalrymple, 2002). To gain a better understanding of MSL change, historic records of water surface elevations are gathered from gauges in the study areas and projected over the lifetime of a proposed project.

### *2.2.1 Flow and Transport Patterns*

Seasonal wind and wave conditions discussed in Sections 2.1.2.1 and 2.1.3.1 drive circulation patterns that dominate sediment transport within the San Juan pocket beaches. Predominant flow direction documented by Kaye (1959), Figure A-46, and Hughes (2005), Figure A-47, show pathways directed from northwest to southeast due to summer trade winds and northern nor'easters. Sediment moves during these times from the east to the west within the pocket beaches, but transport from west to east is much less frequent. West-to-east flow is typically dominated by intense hurricanes to the west of the island (Diaz and Canals, 2019), and hurricane seasons that lack hurricane activity west of this area yield an energy deficit from the west-northwest. Bathymetric and topographic features in and around the San Juan study area may be influenced more dynamically than these reports show (i.e., the Ocean Park hot spot) since they are regional and average (i.e., long(er)-term) model results instead of local, more refined modeling results. Further, data detailed in Section 1.3.1.2.1 and long-term shoreline estimates (Section 2.2.2) indicate a net-zero transport flux within pocket beach cells between rocky headland features.

Winter nor'easters can drive flow and sediment transport patterns in Rincón directing flow from north to south, but intense summer hurricanes that move through the Caribbean Sea south of the island can direct sediment transport south to north. Critically eroded shorelines with minimal sediment in the system mean the study area shoreline in Rincón is likely to remain critically eroded unless sand is introduced to the system synthetically or structures are moved landward from the current shoreline position.

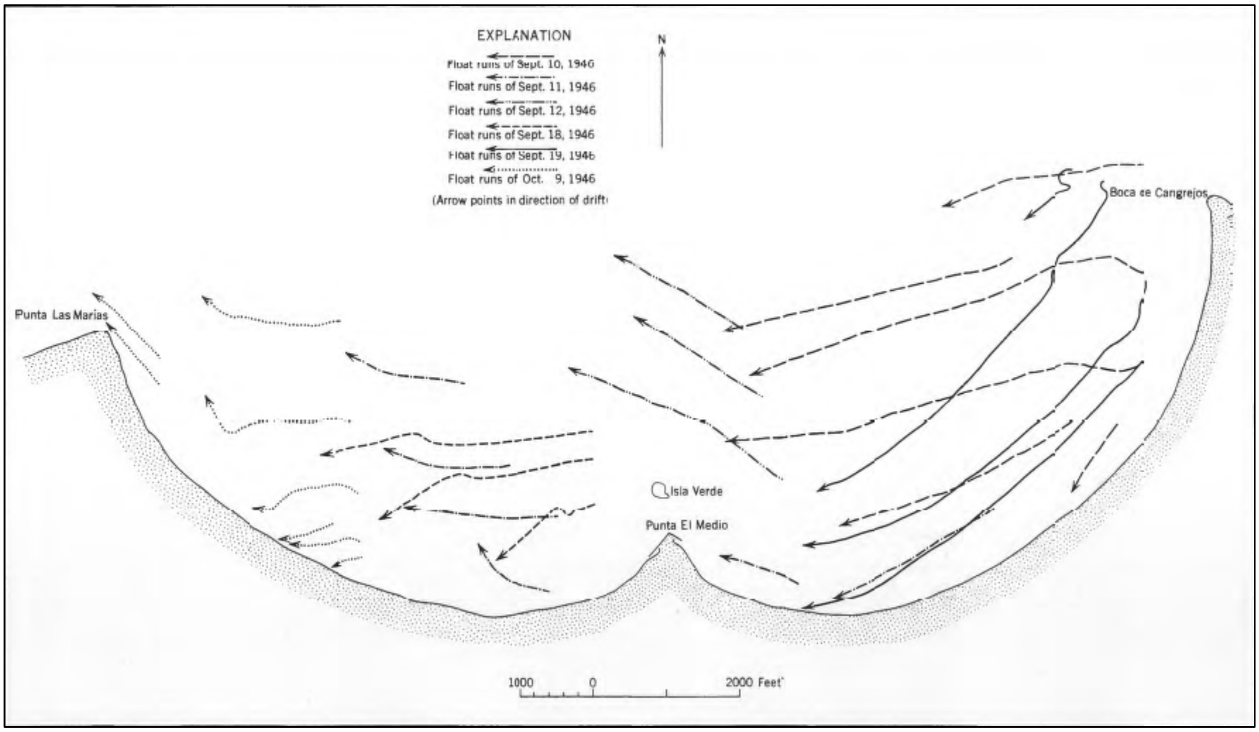


**Figure A-46. General Flow Direction within San Juan Pocket Beaches (Kaye, 1959)**

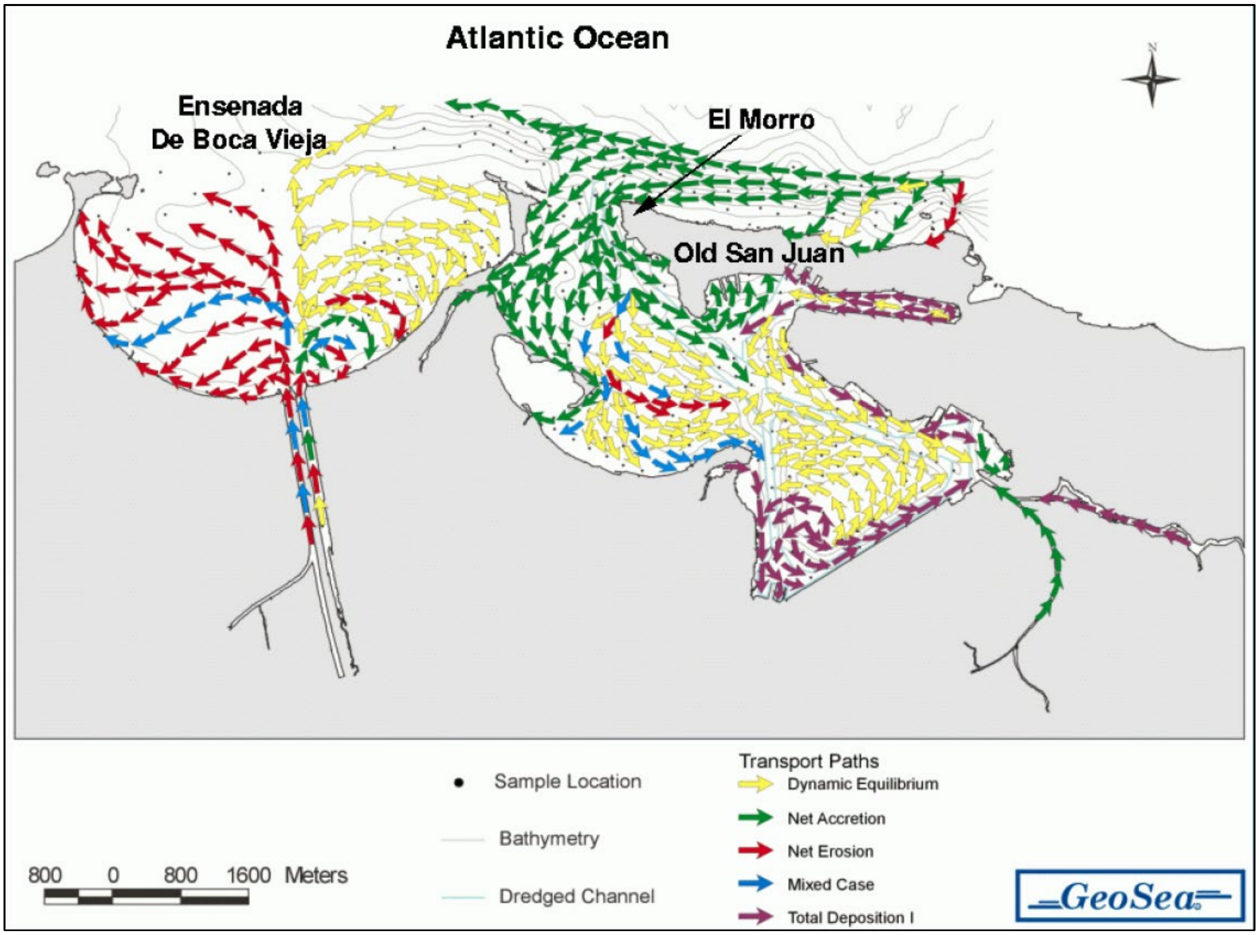


**Figure A-47. General Transport Pathways around San Juan (Hughes, 2005)**

### *2.2.2 Long-Term Shoreline Evolution*

Long-term is a relative phrase. Regarding shoreline change data along the sandy shorelines in Puerto Rico, 50 to 75 years is considered “long-term” data since this is the longest period of record for shoreline changes around the island. Long-term shoreline evolution information for the study areas for the Puerto Rico Coastal Study include aerial imagery compiled and hosted at the CostaVisPR (2019) website and the reports released by Thieler et al. (1999 and 2007). These resources show that beach evolution for the Isla Verde, Ocean Park, and Condado beaches in San Juan somewhat contrasts that of Rincón. CostaVisPR (2019) hosts historic aerial imagery from 1930 to 2019 that shows the beaches from Condado to Isla Verde in San Juan contain generally unchanged beach widths seaward of the vegetation line (Figure A-48). Overlaying aerials from 1950 and 2019 in the study area for Rincón show general shoreline erosion over the last 70 years (Figure A-49). Thieler et al. (2007) built off decades’ worth of work (i.e., Thierler, 1999) to quantitatively assess shoreline erosion in Rincón from 1936 to 2006. Figure A-50 shows an average shoreline change in this area is reported as -0.4 m/yr (-1.3 ft/yr), but 50 percent uncertainty is tied to this number (+/- 0.2 m/yr; +/- 0.6 ft/yr). Other reports with shoreline change data over shorter periods are available (as noted in Section 1.2) that generally confirm the long-term evolution shown below (notwithstanding shoreline change hot spots). Notably, Section 4.2.2 further details the data used in modeling-specific background (historic) erosion rates.

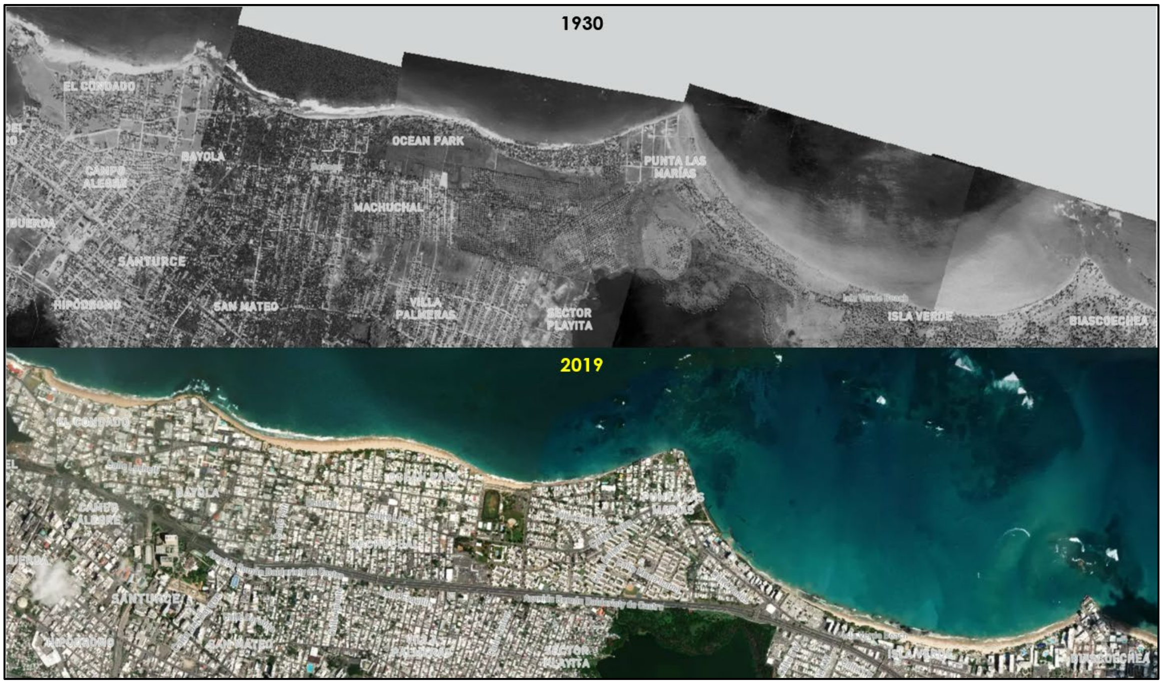


**Figure A-48. Long-term Shoreline Change in San Juan (CostaVisPR, 2019)**


**Figure A-49. Long-term Shoreline Change in Rincón (CostaVisPR, 2019)**

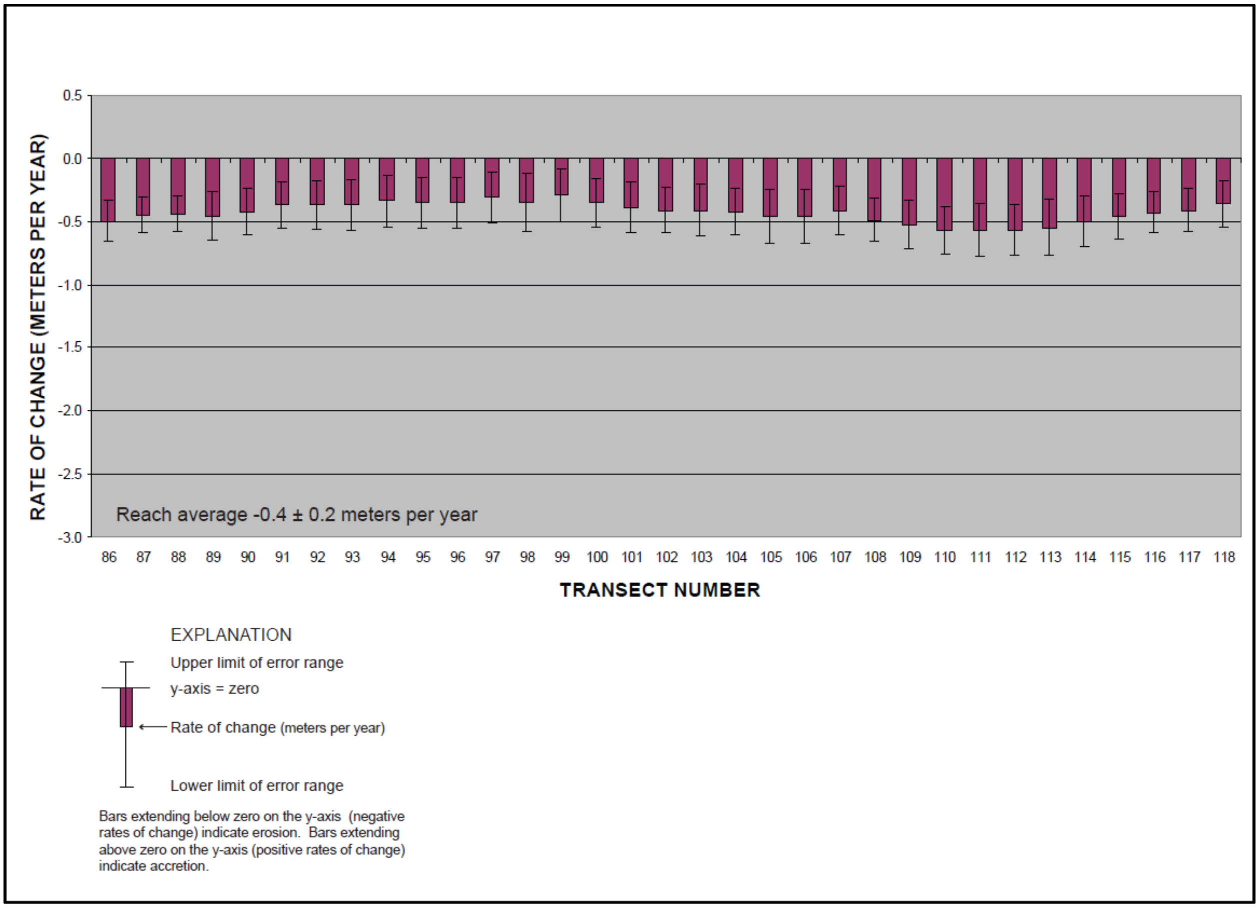


**Figure A-50. Long-term Shoreline Change in Rincón (Thieler, 2007)**

### *2.2.3 Relative Sea-Level Change*

Relative SLC is the net long-term change in sea level with respect to vertical land movement (VLM), including the lowering or rising of land through geologic processes such as subsidence and glacial rebound. Puerto Rico is experiencing a net long-term rise in relative SLC and it is anticipated to continue to rise over the next 100 years. Elevated mean water levels generally yield larger wave heights, more wave runup, and more overtopping, which can accelerate shoreline impacts.

USACE Engineer Pamphlet (EP) 1100-2-1 (USACE, 2019a) and Engineer Regulation (ER) 1100-2-8162 (USACE, 2019b) provide the framework for SLC assessment in all USACE civil works projects. These guidance documents aid planning studies by outlining the National Research Council's (NRC) 1987 assessment of SLC (among other considerations), which advises feasibility studies consider the high probability of a net increase in global MSL. The NRC recommended three scenarios that project future SLC to the year 2100: a low prediction of 0.50 meters (1.64 feet), an intermediate estimate of 1.00 meter (3.28 feet), and a high prediction of 1.50 meters (4.92 feet; USACE, 2019a). This detailed assessment resulted in the NRC's formula that considered the time-varying form of eustatic SLC. USACE (2019a) updated the 1987 projections using the current tidal epoch (1983-2001) and included the most accurate global MSL change at that time to yield Equation 1 below. Note that the preceding equation does not consider local VLM; thus, VLM is added to (or subtracted from) each curve if applicable.

$$E(t_i) = \mathrm{a}(t_2 - t_1) + b(t_2^2 - t_1^2) \qquad \text{(Equation 1)}$$

Where:

- $E(t_i)$ is the relative SLC projected from the median tidal epoch year (1992) to a future planning date in meters; 0.0017 is the USACE global MSL change in meters per year (m/yr)
- $a$ equals 0.0017 and is the USACE global MSL change in meters per year (m/yr); this parameter is modified to local conditions by assigning the local linear historic relative SLC trend
- $t_1$ is the time between the construction date and 1992 in years
- $t_2$ is the time between a future planning date and 1992 in years
- $b$ is a constant that varies by NRC SLC scenario in meters per year (m/yr): 0.0 m/yr representing the historic rate of SLC (USACE "low"), 2.71x10-5 m/yr for the NRC I curve (USACE "intermediate"), 7.00x10-5 m/yr for the NRC II curve (not used in USACE guidance), and 1.13x10-4 m/yr for the NRC III curve (USACE "high")

The equation above needs ending dates to project SLC into the future. USACE (2019a and 2019b) suggests a project's life can be considered 50 years long for a given planning study. However, one should consider a 100-year planning horizon given the fact that USACE projects can extend past the 50-year economic life cycle that study analyses' project justification. Four dates are important when projecting SLC for a given study area under this guidance: the project "base" year: (1) 1992 is the mid-point of the referenced epoch (1983-2001) and is the MSL elevation of zero in which the SLC values are relative to, (2) the year that the project's construction is assumed to be completed, (3) the end of the economic period of analysis which is 50 years following construction completion, and (4) the project's adaptation horizon, which is 100 years following construction completion to adapt to climatological changes. The base year for this study is 2029, the 50-year economic period of analysis is through 2078, and the 100-year adaptation horizon is through 2128.

#### 2.2.3.1 Relevant Tools

USACE has developed two web-based SLC tools to enhance risk-based decision confidence: A Sea-Level Change Curve Calculator and the Sea-Level Tracker. Both tools provide a consistent and repeatable method to visualize coastal water levels due to varying sea levels, allow the user to compare SLC curves, and support simple exploration of how SLC has or will intersect with local elevation thresholds related to infrastructure (i.e., roads, power generating facilities, dunes, and buildings). Taken together, decision makers can align various SLC scenarios with existing and planned engineering efforts, estimating when and how the sea level may impact critical infrastructure and planned development activities (USACE, 2018).

Extreme water levels incorporated into the Sea-Level Change Curve Calculator are based on statistical probabilities using recorded historic monthly extreme water level (EWL) values. NOAA Technical Report National Ocean Service 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, 2013b). The USACE method uses the same NOAA recorded monthly extreme values in a percentile statistical function, and both methods use data recorded and validated by NOAA. The extreme values at the gauge can be significantly different from what may occur at the study site due to differences in site characteristics and complex interactions of physical forces that vary between locations. The level of confidence in the exceedance probability decreases with longer return periods.

The USACE Sea Level Tracker (USACE, 2018) tool provides historic sea-level trends from selected gauges close to the study area that contain a recent period of record. This tool is used to show historical data, such as the MSL monthly 5-year and 19-year moving averages at the gauge along with the USACE low, intermediate, and high SLC Prediction Curves. The SLC trends and curves shown in this report use NOAA gauge data that is projected to the end of 2020 since this was when SLC was analyzed and incorporated into the beginning stages of modeling. These values may be slightly different when this report is published.

#### 2.2.3.2 Trends near San Juan

Monthly MSL data from tide gauges around Puerto Rico are available via NOAA's website. Figure A-51 shows NOAA tide gauges around the island with long-term MSL data, where the two longest records around the island belong to the San Juan, La Puntilla, San Juan Bay, PR NOAA Station 9755371 (discontinuous data since 1962) and the Magueyes Island, PR NOAA Station 9759110 (discontinuous data since 1955). NOAA Station 9755371 provided the MSL trend baseline for the San Juan study area, which lies approximately 3.0 miles west of the Condado shoreline (western-most portion of the San Juan study area) in the San Juan Bay. The MSL trend from 1962 to 2020 for that station is 2.09 mm/yr (0.00686 ft/yr) +/- 0.37 mm/yr (0.00121 ft/yr) at 95 percent confidence (Figure A-52).

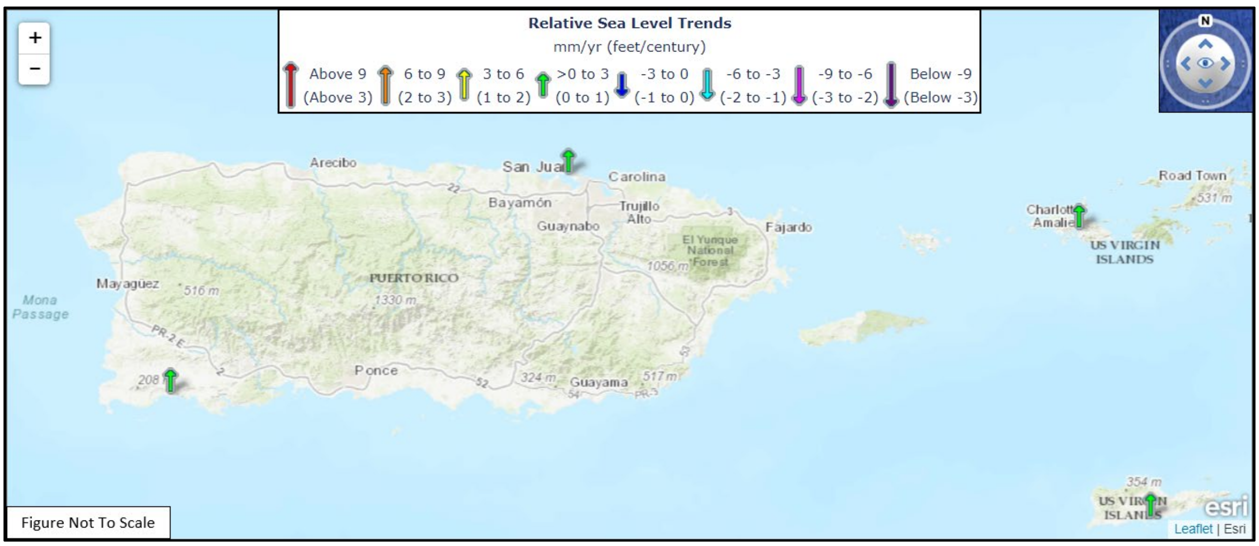


**Figure A-51. Relative SLC Trends around Puerto Rico (NOAA, 2022)**

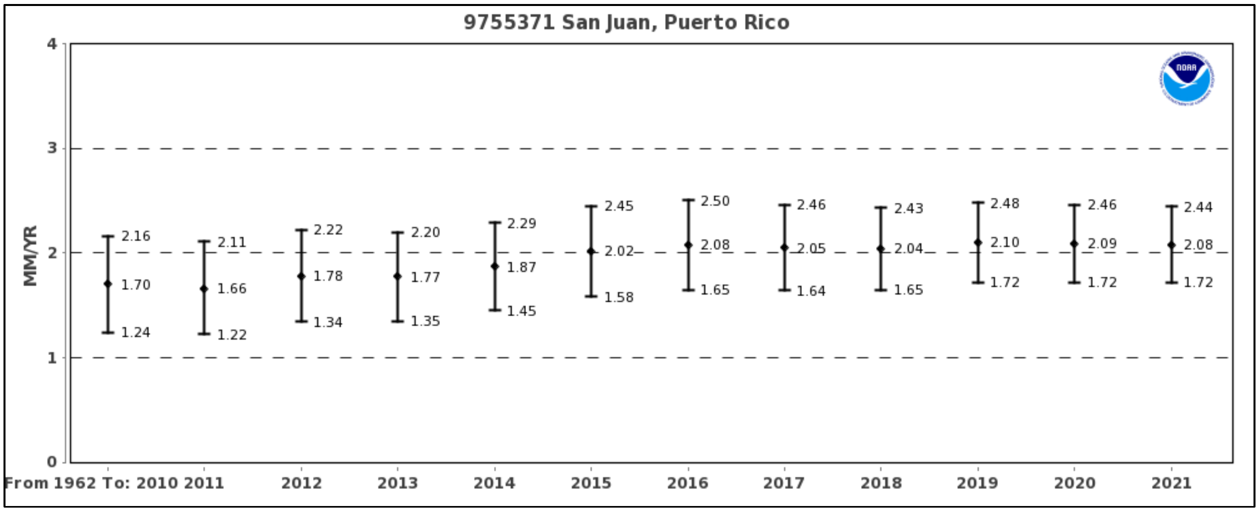


**Figure A-52. SLC Trends at NOAA's San Juan Station over the Past Decade (NOAA, 2022)**

### 2.2.3.3 Projections for San Juan

The USACE low SLC curve simply extrapolates the USACE linear trend, like extrapolating a historic SLC rate as shown in Figure A-53. The regional USACE linear trend for San Juan (SLC Calculator) projected to 0.25 feet by 2019, 0.59 feet by 2078, and 0.93 feet by 2128 (relative to 1992 MSL). The USACE intermediate curve uses the NRC I *b* constant and the SLC equation (Equation 1), listed in Section 2.2.2, to obtain an intermediate SLC projection of 0.29 feet by 2029, 1.25 feet by 2078, and 2.58 feet by 2128. The USACE high curve uses the NRC III *b* constant and the SLC equation (Equation 1), listed in Section 2.2.2, to obtain a high SLC estimation of 0.54 feet by 2029, 3.33 feet by 2078, and 7.79 feet by 2128. Table A-12 and Figure A-54 display this information, where the 5- and 19-year moving averages for San Juan are currently tracking the intermediate SLC curve. However, all three SLC curves were simulated in this study, and adaptation strategies may be developed to mitigate the risk and increased vulnerability based on each TSP alternative's sensitivity to SLC. NOAA (2013a) computed VLM for the San Juan area that yielded very small tectonic vertical shifts from 1962 to 2006 (0.000066 ft/yr or 0.079 inches in 100 years). The sea level trends calculated by NOAA include VLM.

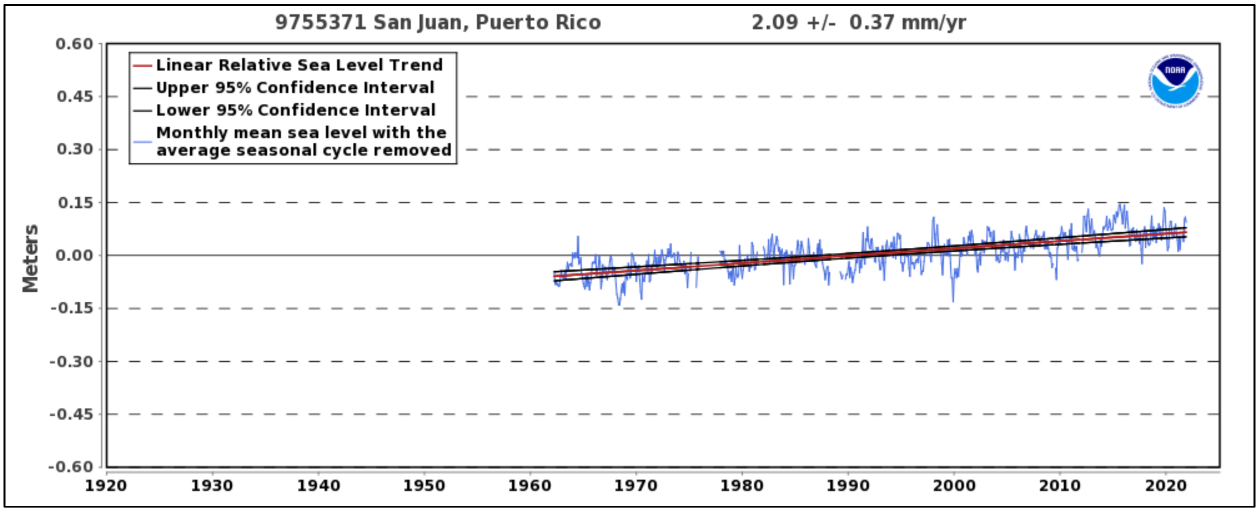


**Figure A-53. SLC Trend at NOAA's San Juan Station**

**Table A-12. SLC Projections in San Juan relative to 1992 MSL**

| Year | USACE Low (Extrapolated NOAA Trend) | | USACE Intermediate (NRC I) | | USACE High (NRC III) | |
|---|---|---|---|---|---|---|
| | m | ft | m | ft | m | ft |
| **2022** | **0.06** | **0.21** | **0.09** | **0.29** | **0.16** | **0.54** |
| 2025 | 0.07 | 0.23 | 0.10 | 0.32 | 0.19 | 0.63 |
| **2029** | **0.08** | **0.25** | **0.11** | **0.38** | **0.23** | **0.76** |
| 2030 | 0.08 | 0.26 | 0.12 | 0.39 | 0.24 | 0.80 |
| 2035 | 0.09 | 0.29 | 0.14 | 0.46 | 0.30 | 0.98 |
| 2040 | 0.10 | 0.33 | 0.16 | 0.53 | 0.36 | 1.18 |
| 2045 | 0.11 | 0.36 | 0.19 | 0.61 | 0.43 | 1.40 |
| 2050 | 0.12 | 0.40 | 0.21 | 0.70 | 0.50 | 1.64 |
| 2055 | 0.13 | 0.43 | 0.24 | 0.78 | 0.58 | 1.90 |
| 2060 | 0.14 | 0.47 | 0.27 | 0.88 | 0.66 | 2.18 |
| 2065 | 0.15 | 0.50 | 0.30 | 0.97 | 0.75 | 2.48 |
| 2070 | 0.16 | 0.53 | 0.33 | 1.08 | 0.85 | 2.79 |
| 2075 | 0.17 | 0.57 | 0.36 | 1.18 | 0.95 | 3.12 |
| **2078** | **0.18** | **0.59** | **0.38** | **1.25** | **1.02** | **3.33** |
| 2080 | 0.18 | 0.60 | 0.39 | 1.29 | 1.06 | 3.47 |
| 2085 | 0.19 | 0.64 | 0.43 | 1.41 | 1.17 | 3.84 |
| 2090 | 0.20 | 0.67 | 0.47 | 1.53 | 1.29 | 4.23 |
| 2095 | 0.22 | 0.71 | 0.50 | 1.65 | 1.41 | 4.64 |
| 2100 | 0.23 | 0.74 | 0.54 | 1.78 | 1.54 | 5.06 |
| 2105 | 0.24 | 0.77 | 0.58 | 1.91 | 1.68 | 5.51 |
| 2110 | 0.25 | 0.81 | 0.62 | 2.05 | 1.82 | 5.97 |
| 2115 | 0.26 | 0.84 | 0.67 | 2.19 | 1.97 | 6.45 |
| 2120 | 0.27 | 0.88 | 0.71 | 2.33 | 2.12 | 6.95 |
| 2125 | 0.28 | 0.91 | 0.76 | 2.48 | 2.28 | 7.47 |
| **2128** | **0.28** | **0.93** | **0.79** | **2.58** | **2.37** | **7.79** |

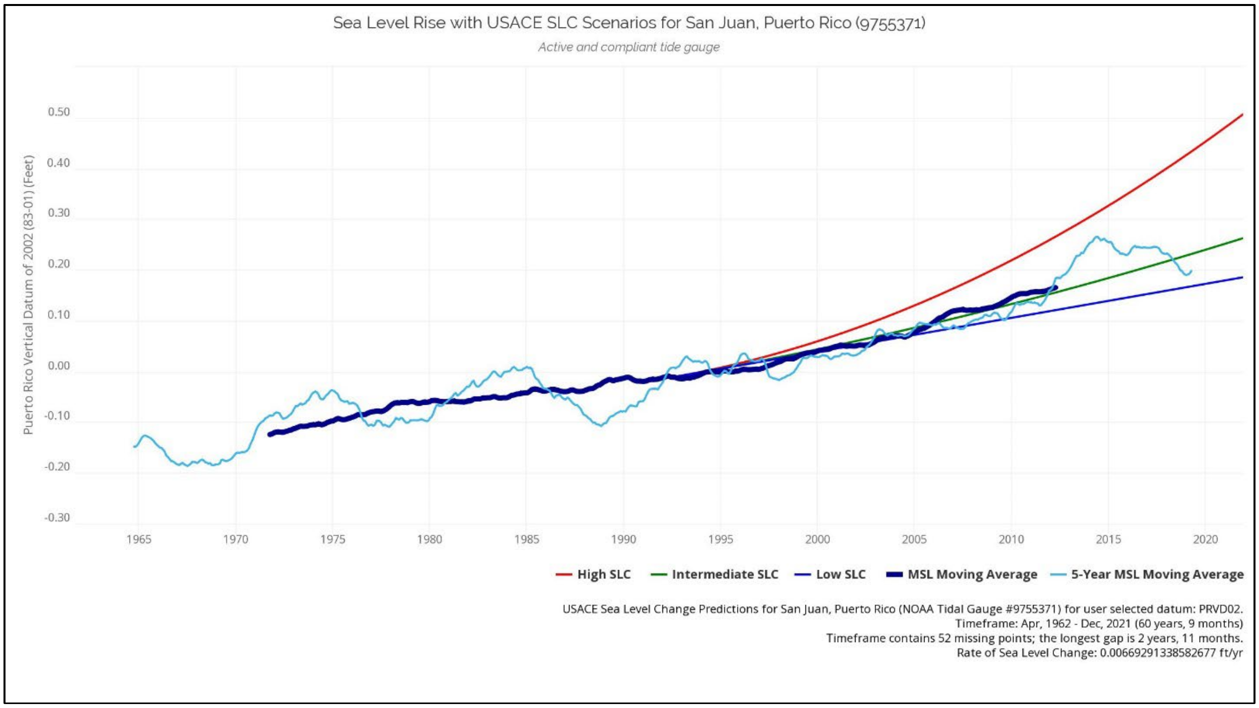


**Figure A-54. SLC Projections with Monthly, 5-year, and 19-year MSL Moving Averages in San Juan**

2.2.3.4 Impact on San Juan Studies

The USACE Sea Level Tracker can plot EWLs and design or terrain thresholds over SLC projections, which is an important step to ensuring that a plan or design can endure and/or adapt to a changing climate over a century. Figure A-55 displays the relative SLC projections (relative to 1992 MSL, which is also 0.0 feet PRVD02) from 2020 to 2128, the NOAA 1 percent AEP above the intermediate curve, and average first-floor elevations (FFE) for Isla Verde (11.9 feet PRVD02), Ocean Park (6.9 feet PRVD02), and Condado (19.0 feet PRVD02). Figure A-56 shows datums and EWL return period values against Ocean Park average FFEs. For reference, local mean sea level (LMSL), referenced in both Figure A-55 and Figure A-56, is also referred to as MSL. Based on the average FFEs, Ocean Park has a relatively low probability of coastal inundation caused solely by the effects of SLC over the next 100 years. Ocean Park is the only area considered in this section since it is the only focus area that currently contains footprints in the TSP (further discussed in Section 4.7).

Optimizing design parameters for potential CSRM measures such as seawall crest elevations will be performed later in the Puerto Rico Coastal Study while considering recent guidance such as Engineering Construction Bulletin (ECB) 2020-6 (USACE, 2022b). Future optimizing analyses could result in proposing project modifications or adaptation strategies (i.e., plan to construct management measures that are designed with the high SLC curve instead of the intermediate SLC curve) to minimize the risk of project failure if SLC rates accelerate in the San Juan study area.

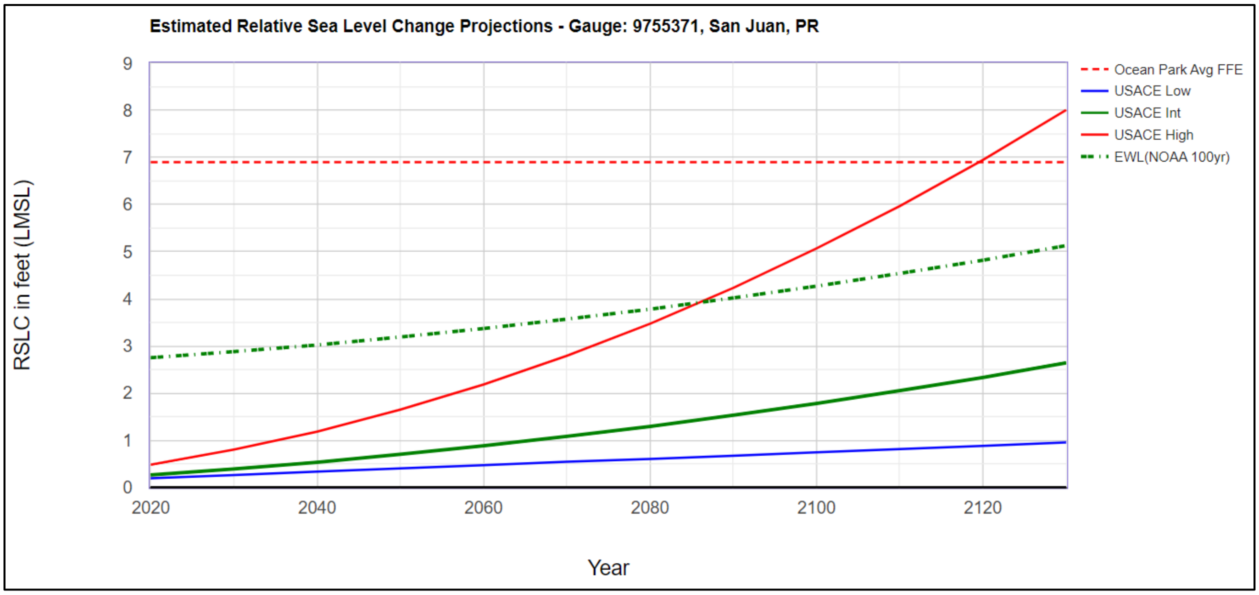


**Figure A-55. SLC vs Average FFEs for Ocean Park (6.9 feet PRVD02)**

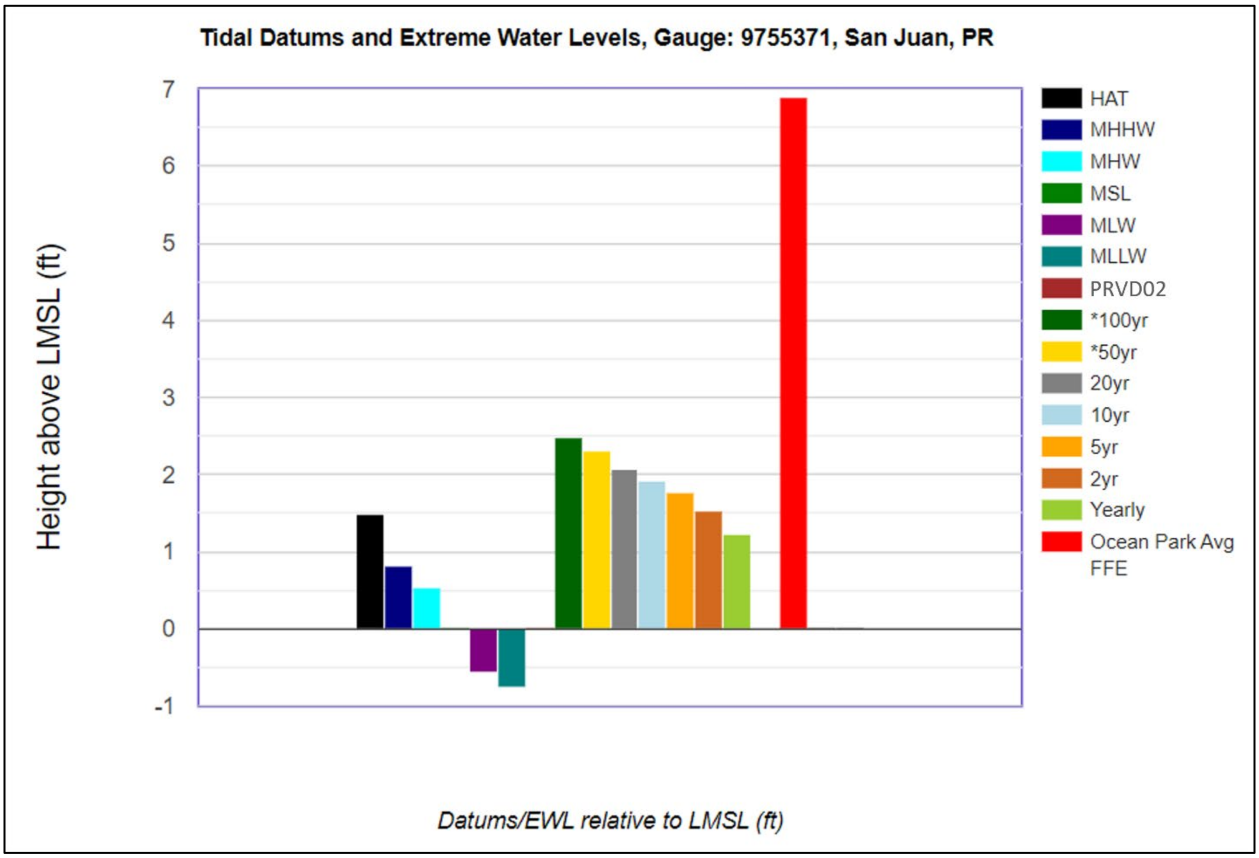


**Figure A-56. Tidal Datums and EWLs for the San Juan Area (* denotes period of record is less than return period)**

#### 2.2.3.5 Trends near Rincón

Like the San Juan study area, USACE, SAJ analyzed monthly MSL data from tide gauges around Puerto Rico and projected potential SLC scenarios out to the 100-year planning horizon. As mentioned previously, Figure A-51 shows NOAA tide gauges around the island with long-term MSL data, where the Magueyes Island, PR NOAA Station 9759110 (discontinuous data since 1955) was used in SLC considerations for the Rincón study area. The Magueyes Island station lies approximately 8.0 miles south-southeast of the Córcega shoreline (southern-most portion of the San Juan study area), and the MSL trend from 1955 to 2020 for that station is 1.90 mm/yr (0.00623 ft/yr) +/- 0.30 mm/yr (0.00098 ft/yr) at 95 percent confidence (Figure A-57 and Figure A-58).

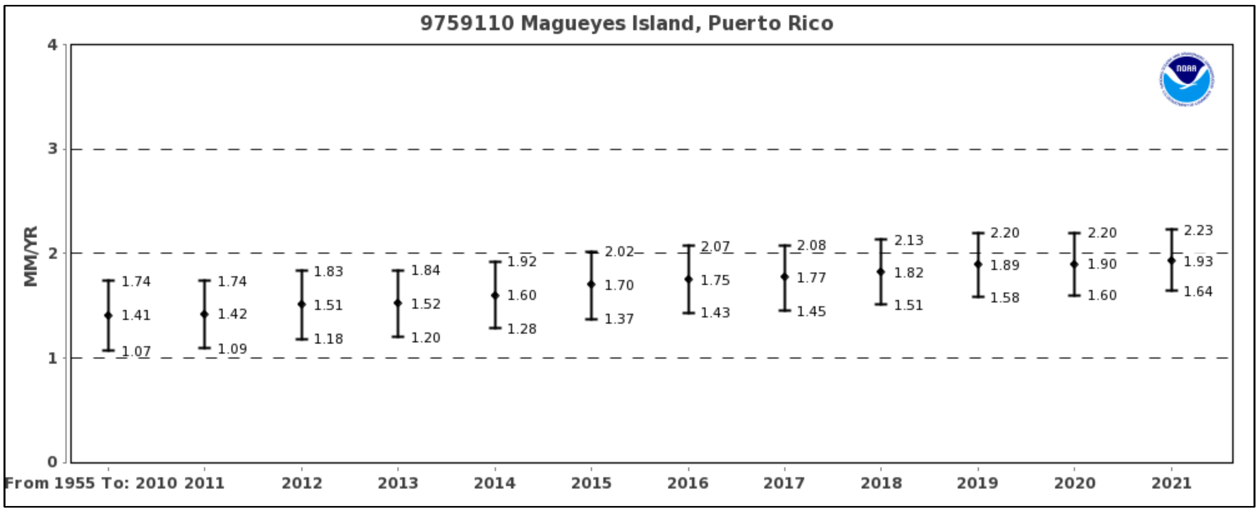


**Figure A-57. SLC Trends at NOAA's Magueyes Island Station Over the Past Decade (NOAA, 2022)**

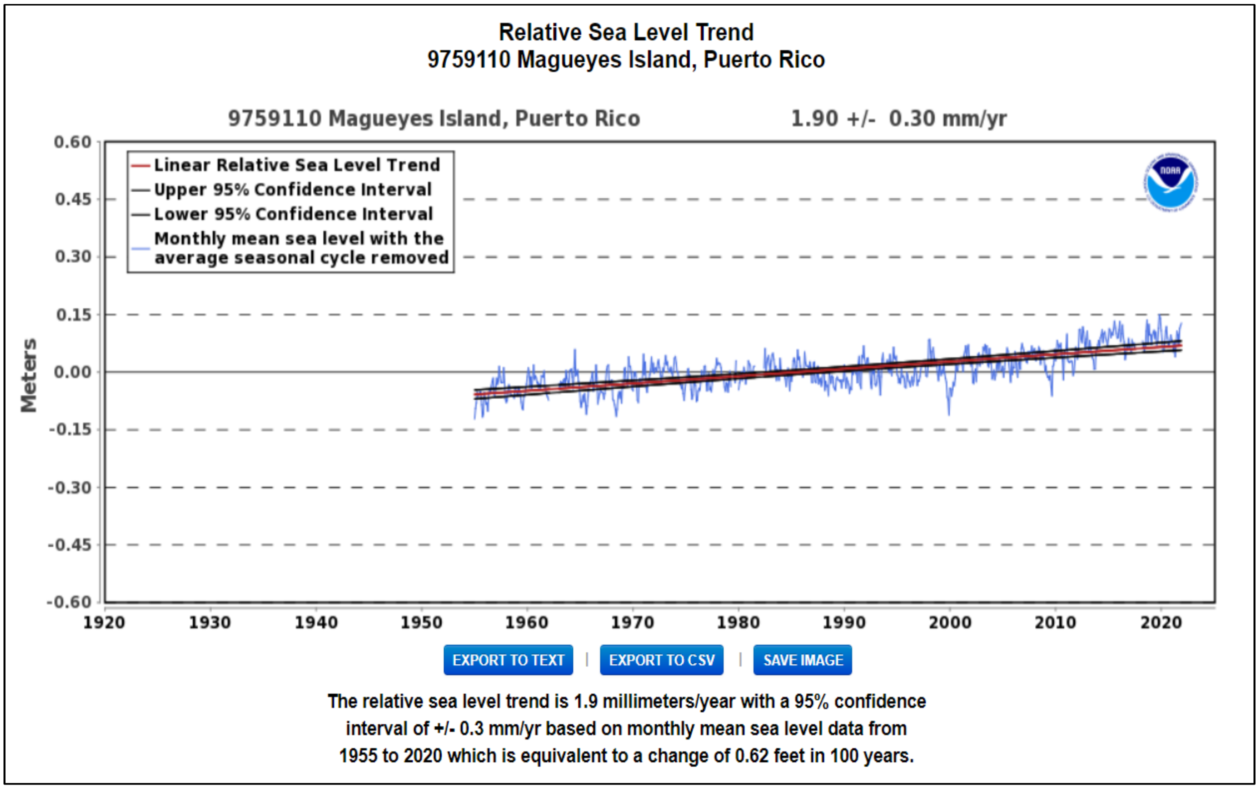


**Figure A-58. SLC Trend at NOAA's Magueyes Island Station**

### 2.2.3.6 Projections for Rincón

Again, like the San Juan study area, USACE, SAJ developed three curves projected to the 2128 (100-year) planning horizon for the Rincón study area. Table A-13 shows that the regional USACE linear trend for the Rincón area projects to 0.23 feet by 2029, 0.54 feet by 2078, and 0.85 feet by 2128 (relative to 1992 MSL) The USACE intermediate curve projects to 0.35 feet by 2029, 1.19 feet by 2078, and 2.49 feet by 2128 The USACE high curve projects to 0.74 feet by 2029, 3.28 feet by 2078, and 7.70 feet by 2128. Figure A-59 displays this information graphically, where moving averages for the Rincón area are somewhat divided. The current MSL elevation and 19-year moving average (light and dark blue lines) are near or under the intermediate SLC curve, but the 5-year moving average suggests more recent water level data is tracking between the intermediate and high SLC curves. However, all three SLC curves were simulated in this study, and USACE, SAJ will develop adaptation strategies to mitigate the risk and increased vulnerability based on each TSP alternative's sensitivity to SLC. NOAA (2013a) computed VLM for the San Juan area that yielded very small tectonic vertical shifts from 1962 to 2006 (0.0016 ft/yr or 1.93 inches in 100 years). The sea level trends calculated by NOAA include VLM.

**Table A-13. SLC Projections for the Magueyes Island Gauge relative to 1992 MSL (Applied to the Rincón Study Area)**

| Year | USACE Low (Extrapolated NOAA Trend) | | USACE Intermediate (NRC I) | | USACE High (NRC III) | |
|---|---|---|---|---|---|---|
| | m | ft | m | ft | m | ft |
| **2022** | **0.06** | **0.19** | **0.08** | **0.27** | **0.16** | **0.52** |
| 2025 | 0.06 | 0.21 | 0.09 | 0.30 | 0.19 | 0.61 |
| **2029** | **0.07** | **0.23** | **0.11** | **0.35** | **0.22** | **0.74** |
| 2030 | 0.07 | 0.24 | 0.11 | 0.37 | 0.24 | 0.77 |
| 2035 | 0.08 | 0.27 | 0.13 | 0.43 | 0.29 | 0.95 |
| 2040 | 0.09 | 0.30 | 0.15 | 0.50 | 0.35 | 1.15 |
| 2045 | 0.10 | 0.33 | 0.18 | 0.58 | 0.42 | 1.37 |
| 2050 | 0.11 | 0.36 | 0.20 | 0.66 | 0.49 | 1.61 |
| 2055 | 0.12 | 0.39 | 0.23 | 0.75 | 0.57 | 1.86 |
| 2060 | 0.13 | 0.42 | 0.25 | 0.84 | 0.65 | 2.14 |
| 2065 | 0.14 | 0.46 | 0.28 | 0.93 | 0.74 | 2.43 |
| 2070 | 0.15 | 0.49 | 0.31 | 1.03 | 0.84 | 2.74 |
| 2075 | 0.16 | 0.52 | 0.34 | 1.13 | 0.94 | 3.07 |
| **2078** | **0.16** | **0.54** | **0.36** | **1.19** | **1.00** | **3.28** |
| 2080 | 0.17 | 0.55 | 0.38 | 1.24 | 1.04 | 3.42 |
| 2085 | 0.18 | 0.58 | 0.41 | 1.35 | 1.15 | 3.79 |
| 2090 | 0.19 | 0.61 | 0.45 | 1.46 | 1.27 | 4.17 |
| 2095 | 0.20 | 0.64 | 0.48 | 1.59 | 1.39 | 4.58 |
| 2100 | 0.21 | 0.67 | 0.52 | 1.71 | 1.52 | 5.00 |
| 2105 | 0.21 | 0.70 | 0.56 | 1.84 | 1.66 | 5.44 |
| 2110 | 0.22 | 0.74 | 0.60 | 1.97 | 1.80 | 5.90 |
| 2115 | 0.23 | 0.77 | 0.64 | 2.11 | 1.94 | 6.38 |
| 2120 | 0.24 | 0.80 | 0.69 | 2.25 | 2.09 | 6.87 |
| 2125 | 0.25 | 0.83 | 0.73 | 2.40 | 2.25 | 7.39 |
| **2128** | **0.26** | **0.85** | **0.76** | **2.49** | **2.35** | **7.70** |

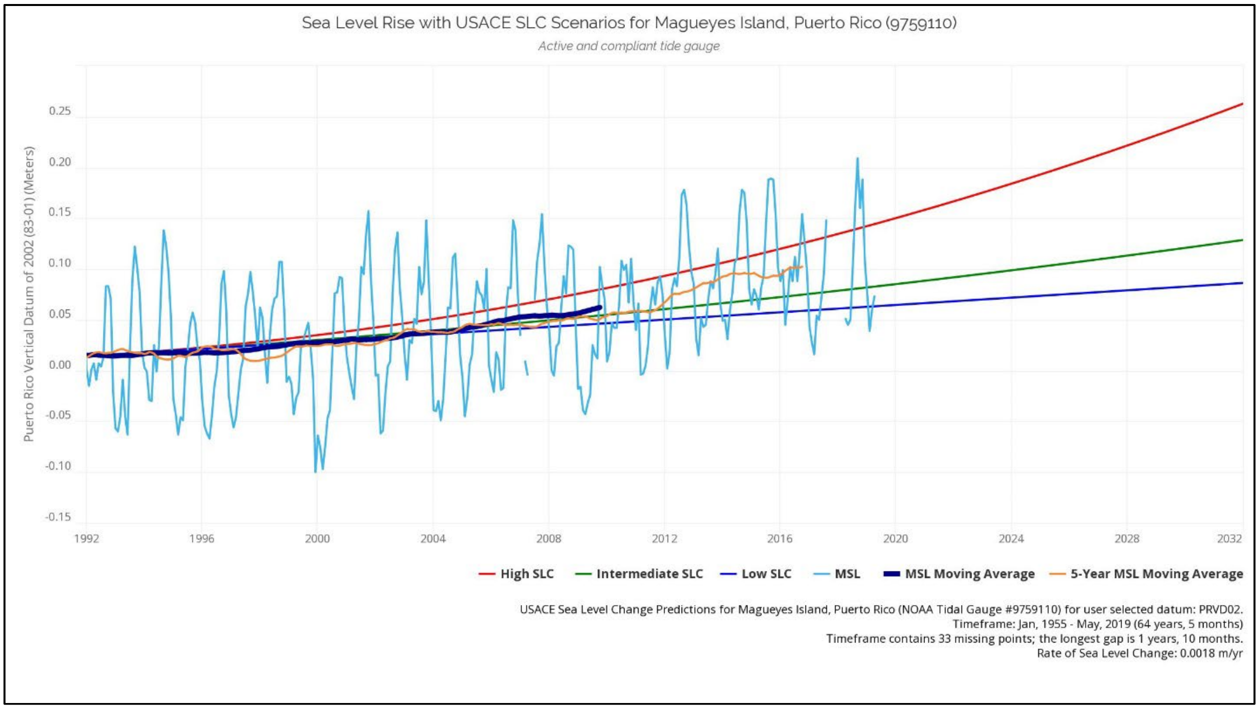


**Figure A-59. Magueyes Island SLC Projections: Monthly, 5-year, and 19-year MSL Moving Averages**

2.2.3.7 Impact on Rincón Studies

Figure A-60 shows the USACE Sea Level Tracker plot with SLC curves (relative to 1992 MSL), the NOAA 1 percent AEP, EWLs, and average FFE (9.6 feet PRVD02) for the Rincón area. Figure A-61 shows the tidal datums and EWLs versus the average Rincón FFE. Both plots show that, based on the average FFEs, Rincón has a relatively low probability of coastal inundation caused solely by the effects of SLC over the next 100 years. However, optimizing design parameters for potential CSRM measures in Rincón will still be performed later in the study while considering recent guidance such as ECB 2020-6 (USACE, 2022b). Future optimizing analyses could result in proposing project modifications or adaptation strategies to prevent inundation due to higher water levels.

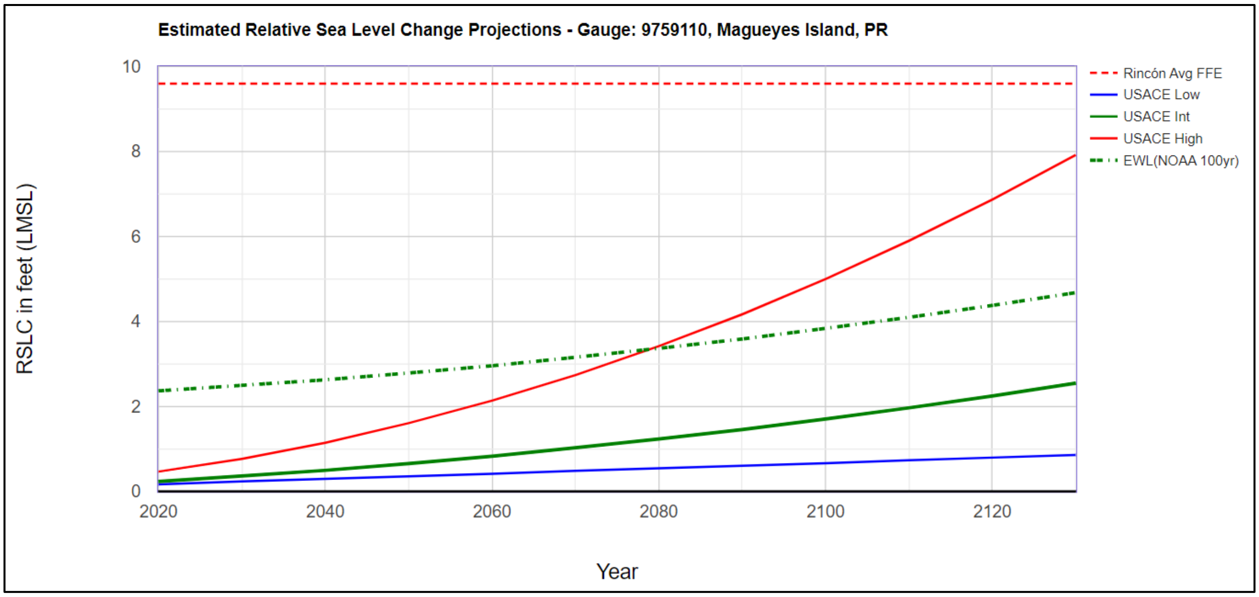


**Figure A-60. SLC Curves vs Average FFEs for Rincón, 9.6 feet PRVD02**

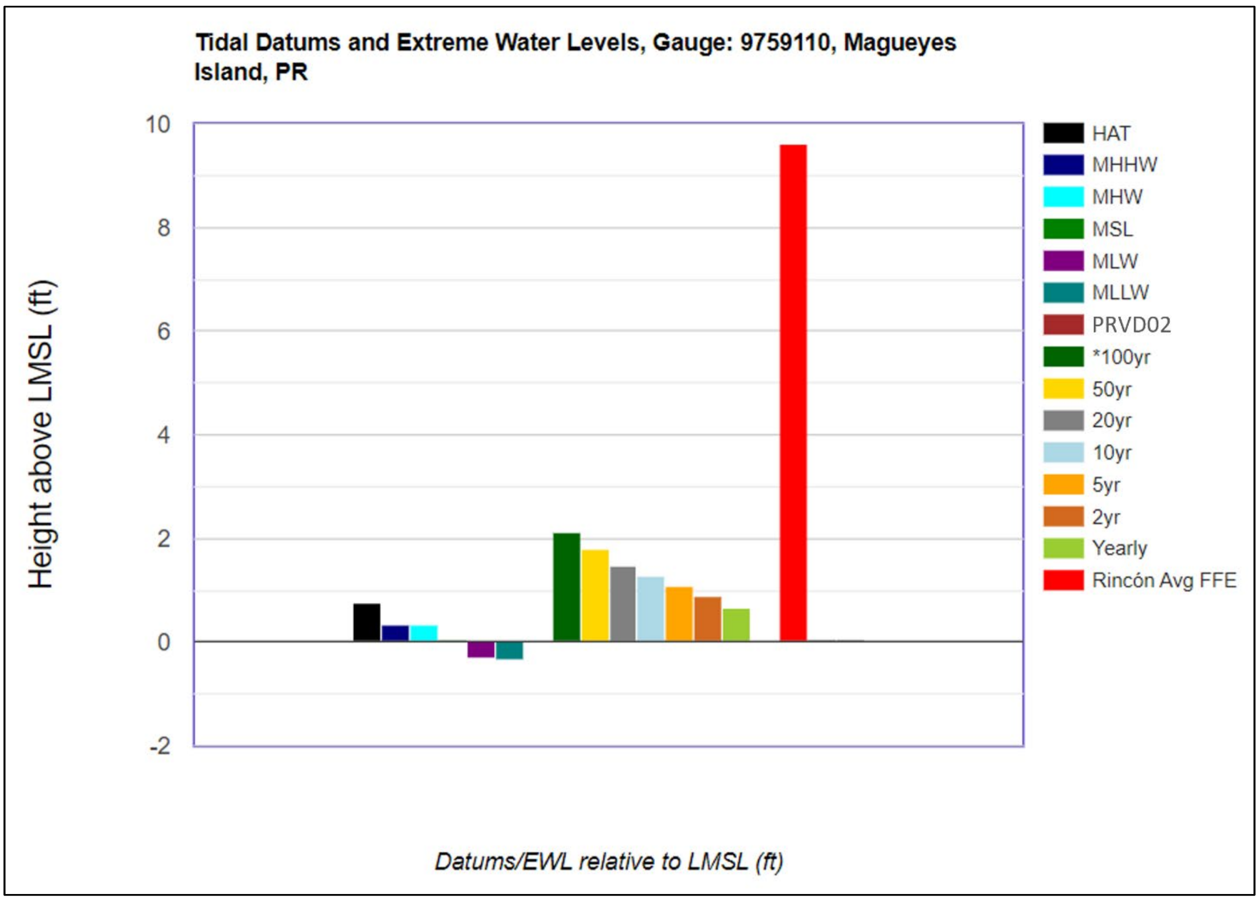


**Figure A-61. Tidal Datums and EWLs for Rincón (*Period of Record is Less Than Return Period)**

## 3 EFFECTS OF ADJACENT FEATURES

Adjacent shoreline and nearshore features, both natural and man-made, have the potential to impact coastal processes in the two study areas. The fringing reef in front of the San Juan study area can mitigate incoming wave energy before that energy fully impacts the shoreline, but not all energy is attenuated. Gaps in the reef can act as wave energy funnels that may introduce higher wave energy at certain portions of the coastline like western and central Ocean Park. Although the fringing reef can help attenuate coastal storm hydrodynamic energy in front of the study area in San Juan, long-period IG waves and surge can propagate into nearby inlets like the San Juan Harbor El Boquerón to the west and Boca de Cangrejos to the east. Elevated water levels from coastal storms can propagate through these inlets into inland waterways and inundate areas behind the study area. While modeling efforts from USACE (2021a) and using HEC-RAS (Section 3.1.1) for areas around the San Jose Lagoon indicate bayside flooding is not likely under the intermediate SLC scenario in this study's San Juan study area, this phenomenon could impact San Juan under higher total water level conditions. These inlets also play a part in the general geology of the San Juan study area by introducing finer riverine sediment to the beaches of Isla Verde, Ocean Park, and Condado. USACE, SAJ sampled larger sediment grain sizes at the western beaches in Condado, but finer-grained sand was present in Ocean Park, and even finer sand was sampled in Isla Verde. This finer sediment is likely from upland rainfall runoff that pushes finer sediment from the Torrecilla Lagoon to nearby coastal beaches.

Shoreline armoring that may have been built too close to the coast also likely play a role in shoreline erosion in both study areas, but historical satellite and aerial imagery indicate the MSL contour along San Juan is generally unchanged over the last century. Inundation focal points in the most vulnerable areas include Barbosa Park and the Marías Skate Park, which may be exacerbated by adjacent coastal construction such as the prominent seawalls and revetments that line adjacent shorelines near Barbosa Park (but do not front Barbosa Bark itself). Nearshore breakwaters and groins, like the small structures just southeast of the Marías Skate Park, may also impound potential feeder beach sand from the pocket of Isla Verde. Upland topography in the San Juan focus area indicates higher elevations in eastern Isla Verde, western Ocean Park, Condado, and extremely low-lying elevations in western Isla Verde and central and eastern Ocean Park. Inundation can pool in these locations, resulting in longer flood-stage durations and higher relative inundation damages to these inland properties. USACE, SAJ did not consider direct or indirect rainfall in this study, but mountainous inland terrain means large rainfall events combined with storms close to (or even far from) the coastline could yield extensive compound flooding to the low-lying areas around the San Juan study area. The primary purpose of the Puerto Rico Coastal Study is to reduce impacts from erosion, surge, and wave events associated with tropical and nor'easter events, however these events are often coincident with rainfall events. Interior drainage for rainfall is outside the scope of this study. Although, per USACE guidance and policy, recommended plans from CSRM studies shall not exacerbate upland inundation due to rain events. Therefore, additional hydrologic and hydraulic analyses in the PED phase should analyze the potential impact from all inundation sources before any structures are built to ensure compliance with guidance and account for any flows that are potentially blocked by proposed features.

Features adjacent the Rincón study area, depicted in Figure A-25, that have the potential to impact study area dynamics include the larger Rincón point to the north from Domes Beach to Punta Ensenada, the Tres Palmas Marine Preserve, the Bajo Blanco sand shoal, a continental shelf very close to the coastline, the Quebrada Los Ramos canal, and extreme upland elevation increase from inland mountainous terrain. Rincón's point from Domes Beach to Punta Ensenada refracts large northerly waves from hurricanes and nor'easters north of the island and attenuates wave energy from the north. Tres Palmas reef also attenuates large northerly wave events and is one of the premier large wave surfing locations in the northeast Caribbean. Mountainous terrain drains upland hydrology to the floodplain just east of Quebrada Los Ramos resulting in high-velocity outflows immediately north of the Rincón study site that are directed by an existing training wall at the mouth of Quebrada Los Ramos. Finer upland and riverine sediment can create turbidity plumes in the nearshore area, but larger beach-quality material may settle in the relatively large sand shoal, Bajo Blanco. A true understanding of sediment transport within the Quebrada Los Ramos and its potential impacts to the coastal system could be further analyzed in PED. Plan Bajo Blanco is relatively shallow compared to the surrounding depths, so this feature may also help to attenuate wave energy from the north. However, sediment deficiencies along the beach directly seaward of the study site indicate sediment from Bajo Blanco does not necessarily make its way to the Rincón study area beach.

## 3.1 Inland Hydrology and Back-Bay Flooding

The primary purpose of a CSRM study is to mitigate or minimize erosion problems and potential storm vulnerability of ocean-fronted coastal structures in a study's location. However, it is important to recognize that other water sources could result in compound flooding and/or residual damages along a coastline. One potential source of inundation includes rainfall-driven inland flooding due to inadequately sized or underperforming stormwater management features (i.e., pumps and gravity discharge structures). For example, stormwater pump failure occurred during Hurricane Maria when the Baldorioty pumps did not remove storm water from Puerto Rico Highway 3 (PR-3), which resulted in storm water backing up into the Ocean Park area (personal communications). This urban stormwater management is the responsibility of the NFS, but potential effects that impact the existing stormwater management system should be considered. For most of the study area, rainfall discharges into the Condado and San Jose Lagoon where existing stormwater outfalls were noted in Condado and Ocean Park. Interior drainage for rainfall is outside the scope of this study. Residual damages from rainfall, compound flooding, and interior drainage represent an inherent risk associated with the study scope. However, per USACE guidance and policy, Recommended Plans from CSRM studies shall not exacerbate upland inundation due to rain events. Therefore, additional hydrologic and hydraulic analyses in the PED phase should analyze the potential impact from all inundation sources before any structures are built to ensure compliance with guidance and account for any flows that are potentially blocked by proposed features.

Assessing flood water flow paths can indicate if bayside flooding may impact a study area, which generally tend to flow from higher elevations to pool in lower elevations. Condado's average upland elevation and average first floor elevation (FFE) in the study area immediately north of the Condado lagoon is roughly 12.0 feet PRVD02 and 18.7 feet PRVD02; thus, bayside flooding is not expected to impact Condado's coastal structures. However, the low-lying areas just north of the San Jose lagoon may allow bay water to flow to the south side of the Isla Verde and Ocean Park study areas. Preliminary hydrodynamic modeling for the San Juan Metro CSRM Feasibility Study showed that the Caño Martín Peña (CMP) Ecosystem Restoration Project (USACE, 2016) is extremely important to bayside water levels in the San Jose Lagoon. Figure A-62 shows the effects on flow and associated bay surge levels through the CMP and in the San Jose Lagoon with and without the dredging project. The associated 1% AEP, based on FEMA relative return periods from the San Juan Metro CSRM Feasibility Study, maximum surge levels within the lagoon when the CMP is dredged is under 3.0 feet PRVD02, which is less than the average elevation around PR-3. Bay water would need to breech PR-3 and propagate roughly 1,500 feet from the lagoon to impact the closest point in the Ocean Park study area (average FFEs in this area are 6.7 feet PRVD02). Further, bay water would need to exceed the average upland elevation of the Isla Verde coastal structures closest to the San Jose Lagoon (roughly 9.0 feet PRVD02) to induce compound flooding in this area. The San Juan Metro CSRM Feasibility Study completely analyzed bayside flooding with the Generation II Coastal Risk Model

(G2CRM) in the San Juan area. Thus, bayside structure inundation damages were assessed for each of the lagoons, including a complete TSP to mitigate bay flooding from the Condado Lagoon.

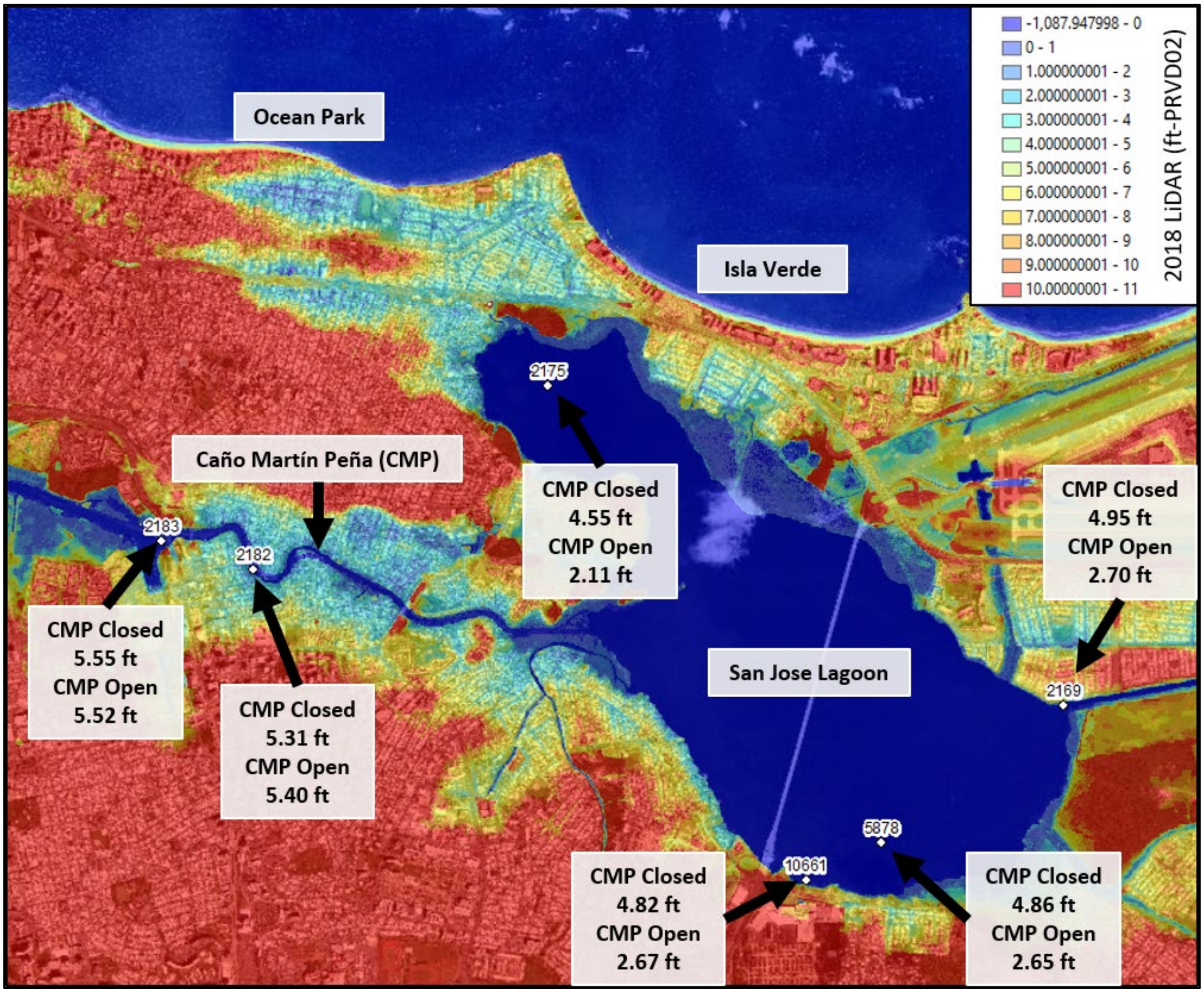


**Figure A-62. 1% AEP Storm Surge Levels with and without the CMP**

### *3.1.1 Hydrologic Engineering Center's River Analysis System (HEC-RAS) Modeling*

The HEC-RAS Version 6.1 modeling software can perform one-dimensional (1D) and 2D hydraulic calculations for a full network of natural and constructed channels and overland flow areas. The 2D functionality was used to perform unsteady-flow hydrodynamic routing to analyze surface water movement due to both coastal and back-bay hydraulic forcing within the study area. USACE, SAJ used the HEC-RAS model for three primary purposes: to assist in a delineation of the G2CRM model domain and refinement of the protective system element (PSE) hydraulic performance, to inform potential risk due to inundation from coastal and back-bay flooding with SLC, and to aid in the determination of potential impacts to other social effect (OSE) benefits. HEC-RAS simulations were performed for the segment of Isla Verde and Ocean Park, which are highly susceptible to overland flow due to the topography of the area that generally slopes away from the shoreline creating an area for which water may begin to pond within the protected area. The Condado reach does not share this topographic trend, and the San Juan Metro Study provides a solution for back-bay flooding residual risk in this area. Similarly, Rincón has no back-bay flooding source and contains an increasing upland elevation, limiting the risk of significant overland flow and inland inundation.

#### 3.1.1.1 HEC-RAS Model Development

USACE, SAJ defined the HEC-RAS model domain using an estimated inundation extent based on topographic data and imagery from historic floods from storms such as Hurricane Maria. USACE constructed the entirety of the model domain using a 2D flow area with 30-foot by 30-foot computation point spacing (grid cell size). The terrain file, 2018 LiDAR dataset, assisted in the establishment of the grid cell geometric and hydraulic properties. Breaklines, with a more refined grid cell spacing of 10 feet by 10 feet, were used to define any potential barriers to flow, such as roads or high ground.

The model is intended for unsteady flow conditions using inflow boundary conditions. USACE, SAJ input an external boundary condition, representing either the coastal or back-bay water levels, as stage-hydrographs. HEC-RAS used the diffusion wave equation, which is the default equation within RAS and appropriate for a feasibility level analysis. Figure A-63 below depicts the model geometry.


**Figure A-63. HEC-RAS Model Domain for Isla Verde and Ocean Park**

Surface roughness coefficients (Manning's n value) were estimated using the National Land Cover Database 2006 for Puerto Rico. Figure A-64 shows the National Land Cover Database land use coverage for the study area. Aerial images of the study area show minimal changes in land cover from 2006 to 2020; therefore, the 2006 land coverage should be a good representation of the project conditions. Table A-14 shows the Manning's n values used for each land cover.

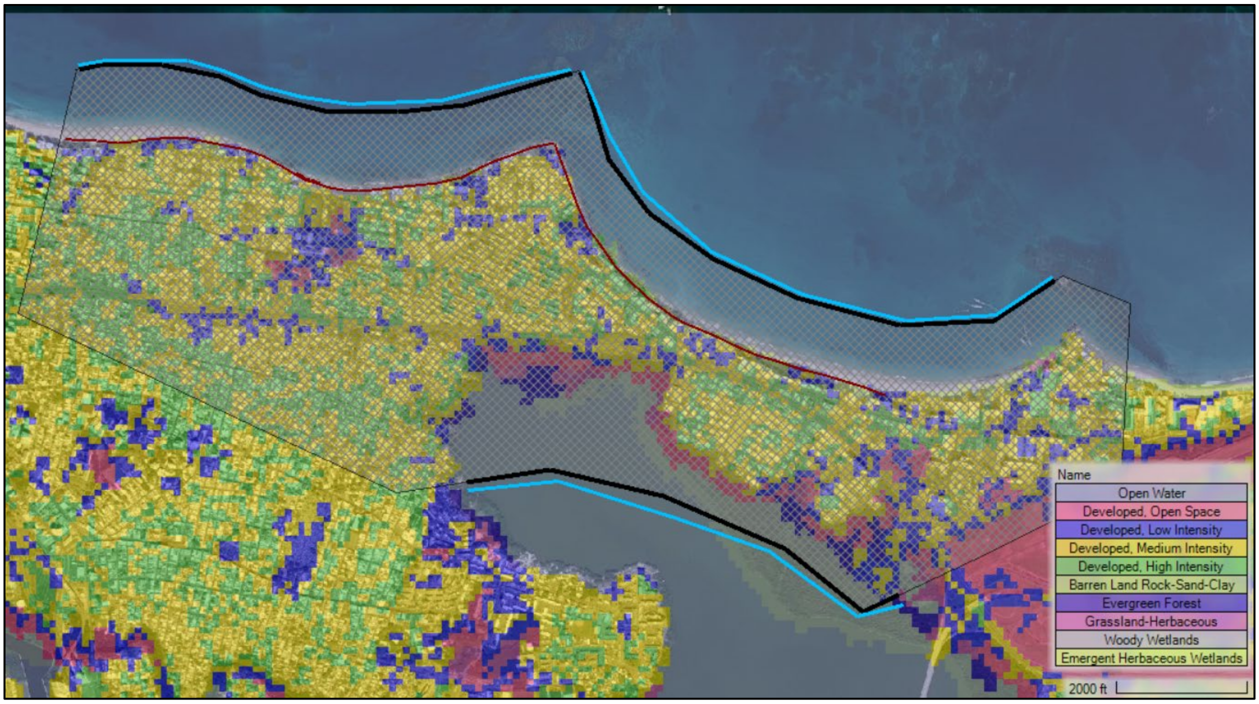


**Figure A-64. HEC-RAS Model Manning's n Map Layer**

**Table A-14. Land Covers Manning's n Coefficient**

| Land Cover | Manning's n Coefficient |
|---|---|
| Barren Land | 0.025 |
| Cultivated Crops | 0.035 |
| Development, High Intensity | 0.150 |
| Development, Medium Intensity | 0.080 |
| Development, Low Intensity | 0.100 |
| Development, Open Space | 0.040 |
| Emergent Herbaceous Wetland | 0.070 |
| Evergreen Forest | 0.160 |
| Grassland | 0.035 |
| Open Water | 0.040 |
| Pasture | 0.030 |
| Shrub | 0.100 |
| Woody Wetlands | 0.120 |

No observed hydrologic data, including stage or flow, can be used for model calibration, therefore the HEC-RAS model developed was not calibrated. USACE, SAJ used best engineering practices and judgment for the selection of the model parameters to obtain adequate model results. The model used standard values for Manning's roughness that were dependent on land use. To reduce errors based on terrain data the model incorporated breaklines and cell spacing adjustments. USACE, SAJ constructed the model domain to ensure the 2D mesh extents did not constrain the interior flooding footprint, i.e., no “glass-walls” or areas of undefined topographic coverage where flood paths could reach.

#### 3.1.1.2 Determining Inland Flooding Extent in Isla Verde and Ocean Park

The primary purpose of the HEC-RAS model was to assess storm-surge propagation, specifically inland inundation extent and depths, within the Isla Verde and Ocean Park study areas. HEC-RAS simulations were performed for multiple scenarios, including the lowest frequency coastal surge event (computed as part of the Beach-*fx* storm suite) and a similar frequency back-bay surge event (computed as part of the CHS dataset). Additionally, 50 years of intermediate SLC was simulated in conjunction with these events. The final inundation extent from the coastal event plus 50 years of intermediate SLC, as shown in Figure A-65, were used to delineate the G2CRM model domain and confirm the Beach-*fx* reach lengths.

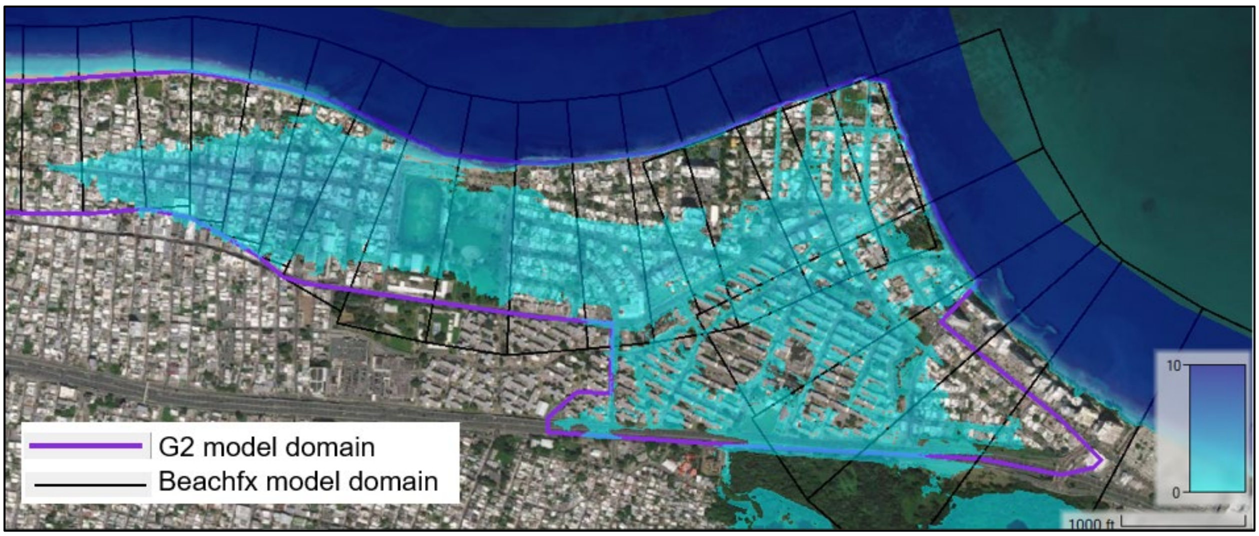


**Figure A-65. HEC-RAS Results Using 0.71% Water Level AEP Plus MHHW Plus 50- year Intermediate SLC**

The HEC-RAS model also assisted in determining the appropriate PSE values with G2CRM. USACE used an iterative process to estimate the PSE elevation and length, perform model simulations, extract peak water surface elevations, and compare to peak water surface elevations from HEC-RAS for comparable storm events. USACE repeated this process until the PSE elevation and length produced maximum stage results that were comparable to the RAS model. This was necessary as G2CRM has limited capabilities to simulate hydraulic processes, especially across a coastline with highly variable elevations. Therefore, HEC-RAS was used to perform 2D unsteady flow at a higher resolution to assess the potential flood path propagation and compute the maximum inundation depths and extents more accurately. The HEC-RAS model was used as a comparative data point to ensure the PSE values were simulating peak water surface elevations within the protected area as accurately as possible.

#### 3.1.1.3 Back-Bay Residual Risk

USACE, SAJ evaluated the back-bay surge event with 50 years of intermediate SLC for the purpose of understanding potential residual risk and impacts to project benefits. USACE simulated the back-bay surge event as a boundary condition to the HEC-RAS model using the same model build used to assess the coastal storm propagation (described in Section 3.1.1.2). The model used CHS output within the San Jose Lagoon for a storm frequency like the lowest frequency storm event (coastal forcing) from the Atlantic Ocean. The results, shown in Figure A-66, illustrate that residual risk is generally low due to back-bay flooding with intermediate SLC, and therefore plan formulation will not occur along the back-bay. The HEC-RAS runs determined that a back-bay SWE above 4.7 feet PRVD02 may cause impacts to the structure inventory, indicating potential back-bay inundation risk in this area. Thus, USACE removed residual damages from back-bay flooding from the total damages by running a separate back-bay storm suite in G2CRM under the high SLC scenario.


**Figure A-66. HEC-RAS Results Using 0.40% Water Level AEP Plus MHHW Plus 50- year Intermediate SLC**

#### 3.1.1.4 Impacts to Other Social Effects

Additionally, USACE extracted the maximum inundation (water surface elevations) and stage-duration time series results from the HEC-RAS model to support the calculation of OSEs for the comprehensive benefits analysis conducted by Economics. This required the selection of representative locations within each model reach and extracting the data (for the lowest frequency coastal event) within RAS Mapper. The stage-duration results provide insight into the recession rates of flood waters within the Isla Verde and Ocean Park study areas to determine the potential number of days that flooding may disrupt businesses, homes, roads, etc.

## 4 PROBABLISTIC LIFE-CYCLE PLANNING MODELS

Federal participation in CSRM projects is generally based on assessing four principle and guideline (P&G) procedures, which are commonly referred as “the four accounts”: National Economic Development (NED), environmental quality, regional economic development, and OSEs. Three of the most relevant USACE guidance documents that detail these accounts and how to successfully plan for an efficient and effective CSRM project include the U.S. Water Resources Council’s (WRC) P&G implementation paper (WRC, 1983), the Institute for Water Resources’ (IWR) Planning Manual (Yoe and Orth, 1996), and the IWR’s white paper on applying the four accounts in federal planning studies (USACE, 2008a). These documents explain how planning studies should explore holistic, intergovernmental, and inter-sectored solutions to federal water resources problems, and CSRM plans are typically selected with favorable economic justification in which the benefits of a project outweigh the costs of that same project. Analyzing something like a project’s benefit to cost ratio (BCR) requires both engineering (project performance and evolution) and planning (alternative analysis and economic justification) analyses. However, the interdependence of these functions applied in various coastal environments around the world can result in difficult and arduous assessments and computations without the assistance of computer-based modeling. Thus, USACE developed life-cycle simulation models, Beach-*fx* (Rogers et al., 2009) and G2CRM (USACE, 2017b and USACE, 2018b), to evaluate flood risks and damages without a project and to evaluate CSRM measures and alternatives.

Beach-*fx* quantifies coastal storm-driven flooding, wave attack, and erosion damage to shorefront structures, whereas G2CRM only quantifies coastal storm-driven flooding but can evaluate flooding further inland than Beach-*fx*. Thus, both models were applied to fully evaluate coastal risk in the study area.

Both Beach-*fx* and G2CRM combine the evaluation of physical performance and economic benefits and costs of CSRM projects to form the basis for determining the justification for 50 years of federal participation. They are event-driven, life-cycle models that use a Monte Carlo simulation technique to estimate the economic performance of a future project (i.e., estimating future outcomes by randomly applying historic storms to the coastal environment). USACE guidance (USACE, 2019c) requires that CSRM studies include risk and uncertainty. These models satisfy this requirement by fully incorporating risk and uncertainty throughout the modeling process (input, methodologies, and output). Over the 50-year period of analysis, the models estimate damage incurred from a series of storm events with defined AEPs. These plausible storms, the driving events, are randomly generated using a Monte Carlo simulation approach.

While both models were developed for CSRM studies with a similar approach (using random storm events to estimate potential damages to structures within a model area), differences in model application include Beach-*fx* being developed for open-coast scenarios (both horizontal forcing and vertical water level changes that yield wave, erosion, and inundation damages) and G2CRM being developed for bayside flooding scenarios (just vertical water level forcing that yield inundation damages). Thus, the Beach-*fx* analysis comprised the first row of structures for this project, and the G2CRM analysis encompassed the inland structures behind the first row with similar input conditions. Climatological forcing and existing features discussed above define input for these models such as storm suites, storm rates, geologic input, shoreline type and elevation input, shoreline evolution input, SLC input, potential management measures, and costing considerations. The existing condition of the study area was then simulated to define the future without-project (FWOP) scenario, and management measures combined to comprise project alternatives for future with-project (FWP) scenarios. Output from both models for all simulations were seamlessly merged for a total CSRM plan in both San Juan and Rincón. Some engineering input parameters between the two models differ for the same location such as subtle storm suite nuances, relative storm probabilities, how flood pathways are input for inland inundation damages, etc. Section 4.3 details these differences further.

## 4.1 Site Identification and Characterization

The first step in Beach-*fx* or G2CRM modeling is identifying the study location and digitizing the study's model area. Alongshore model segmentation and inland model area extents are determined differently for these two models due to nuances in model application. Further, project planning is done by identifying segments of coast called "planning reaches" that may be hydraulically or economically separable. Thus, three separate analysis designations may be used for similar study areas, but all results are reported by the identified planning reaches instead of individual modeling reaches. The information in this section is intended to clarify how the Beach-*fx* and G2CRM models were set up and ultimately included in the overall planning process.

A Beach-*fx* study area is generally represented by alongshore divisions of the shoreline referred to as "reaches" that are usually rectangular in shape with varying cross-shore inland extents. Since the term "reaches" may also be used to describe segments of the shoreline where project alternatives are applied, Beach-*fx* reaches are referred to as "model reaches" in this report. Model reaches are contiguous, morphologically homogenous areas that contain groupings of structures (residences, businesses, walkovers, roads, etc.). Structure groupings within Beach-*fx* model reaches are represented by "damage elements" (DEs), and DEs are grouped within divisions referred to as "lots." Each model reach is ideally represented by a cross-shore profile that defines the cross-shore elevation makeup of that area (Section 4.2 describes profiles for each Beach-*fx* model build further). Model reaches are variable, but they are segmented to provide adequate model resolution. Therefore, most Beach-*fx* model builds require more than one model reach, and areas with complex hydrodynamics or variable terrain may require more than one Beach-*fx* model build. Four total Beach-*fx* model builds with 58 total model reaches were necessary to define the San Juan and Rincón study areas: Nine model reaches from La Ventana al Mar (R1) to Punta Piedrita (R9) represented the Condado Beach-*fx* model area, 22 model reaches from Punta Piedrita (E01) to Punta Las Marias (E22) represented the Ocean Park Beach-*fx* model area, 15 model reaches from Punta Las Marias (R15) to Punta El Medio represented the Isla Verde Beach-*fx* model area, and 12 model reaches from Quebrada Los Ramos (R11) to Corcega (R22) represented the Rincón Beach-*fx* model area. Model reaches in Beach-*fx* contained inland extents (or reach widths), measured from the seaward-most upland point in each reach, that ranged from 1,000 feet in Rincón to 2,000 feet in Isla Verde. Reach widths in Ocean Park and Condado varied with estimated inland inundation extents, like the G2CRM domain delineation described below.

A G2CRM study area is represented by polygon domains that are segmented by areas of similar inundation threshold potential. They are comprised of individual sub-areas (referred to here as "G2CRM model areas") that are delineated based on the separability from possible sources of coastal flooding. Initially, the DEM and the NOAA Sea Level Rise (SLR) Viewer assisted in determining model separability based on the location of various flood sources. In locations with complex topography, as detailed in Section 3.1, HEC-RAS was used to aid in hydraulic pathway definition and model separability for G2CRM. Additionally, HEC-RAS was also used to help define the inland extent of both Beach-*fx* and G2CRM for the more complex upland terrain (i.e., between the San Juan beaches and the San Jose Lagoon). Extreme coastal (roughly the 150-year or 0.007 AEP SWE) and back-bay (roughly the 250-year or 0.004 AEP SWE) CHS events that included high tide (MHHW) and intermediate SLC's project 2077 water level setup were simulated through

HEC-RAS to yield the ideal contour (6.6 feet PRVD02) for which to designate inland domain extremes San Juan. Thus, four total G2CRM model areas were digitized to define the San Juan and Rincón model areas for the Puerto Rico Coastal Study: La Ventana al Mar to Punta Piedrita represented the Condado G2CRM model area, Punta Piedrita to the Maria’s Skate Park represented the Ocean Park G2CRM model area, Maria’s Skate Park to Punta El Medio represented the Isla Verde G2CRM model area, and Quebrada Los Ramos to Corcega represented the Rincón G2CRM model area. Additionally, the Ocean Park back-bay G2CRM model area (only implemented in high-shear, low-CAPE model runs) is represented by the Ocean Park G2CRM model area. G2CRM model areas contain damage elements and lots like Beach-*fx*, but these structures are spatially distributed according to the DEM instead of ideally defined on one-line cross-shore profiles.

Project planning analyses yielded different planning reaches in San Juan than those digitized during initial modeling efforts. Four separable elements, or planning reaches, defined for this study are as follows: La Ventana al Mar to Punta Piedrita represented the Condado planning reach, Punta Piedrita to the Beach-*fx*’s R11/R10 segregation represented the Ocean Park planning reach, R11/R10 to Punta El Medio represented the Isla Verde Planning Reach, and Quebrada Los Ramos to Corcega represented G2CRM’s Rincón model area. Table A-15 and Figure A-67 through Figure A-70 show the Beach-*fx*, G2CRM, and planning areas for San Juan and Rincón accordingly.

**Table A-15. San Juan's General Nomenclature for Modeling and Project Planning**

| Analysis | Alongshore Designation for Comparison by Model Reach | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **R1** | **... West to ...** | **R9** | **E01** | **E02** | **... West to ...** | **E22** | **R15** | **R14** | **R13** | **R12** | **R11** | **R10** | **... West to ...** | **R01** |
| Beach-*fx* 's Extent | Condado | | | Ocean Park | | | | Isla Verde | | | | | | | |
| G2CRM's Extent | Condado | | | Ocean Park | | | | | | Isla Verde | | | | | |
| Planning's Extent[2] | Condado | | | Ocean Park | | | | | | | | | Isla Verde | | |

[1]Rincón's extent is the same for all three designations and ranges from R11 south to R22.

[2]The combined modeling area is the same as the project planning area.

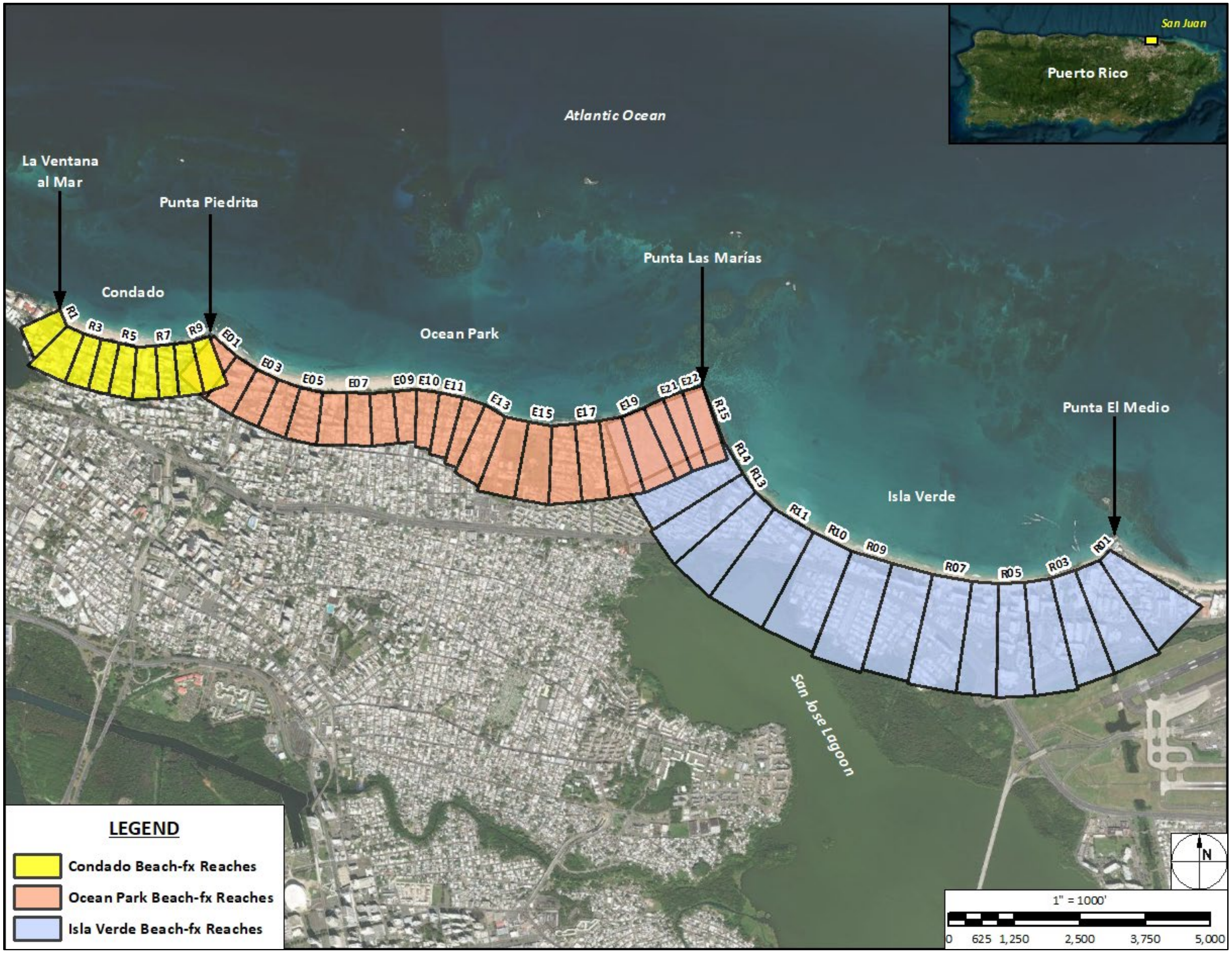


**Figure A-67. San Juan's Beach-*fx* Model Domains**

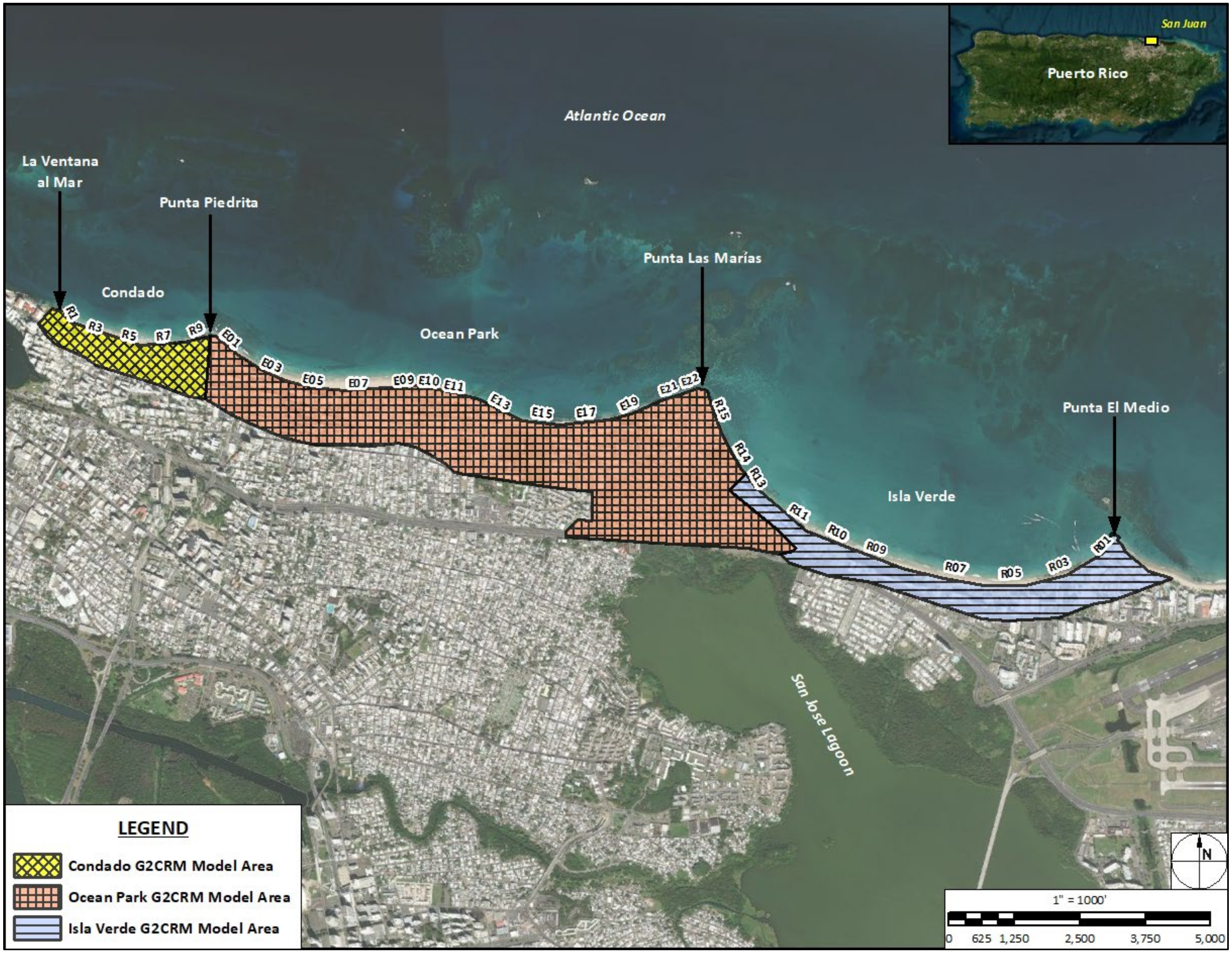


**Figure A-68. San Juan's G2CRM Model Domains**

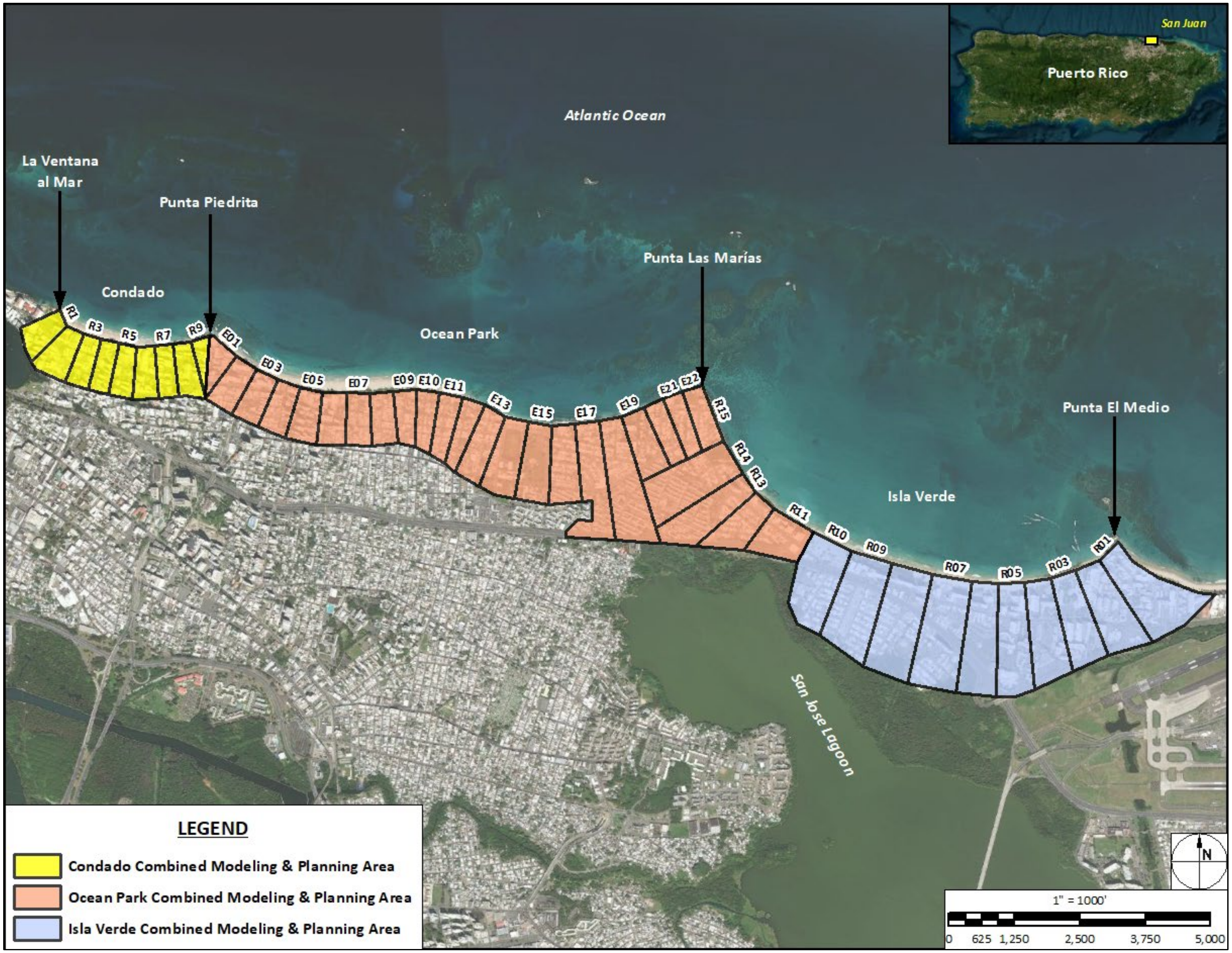


**Figure A-69. San Juan's Planning Domains**

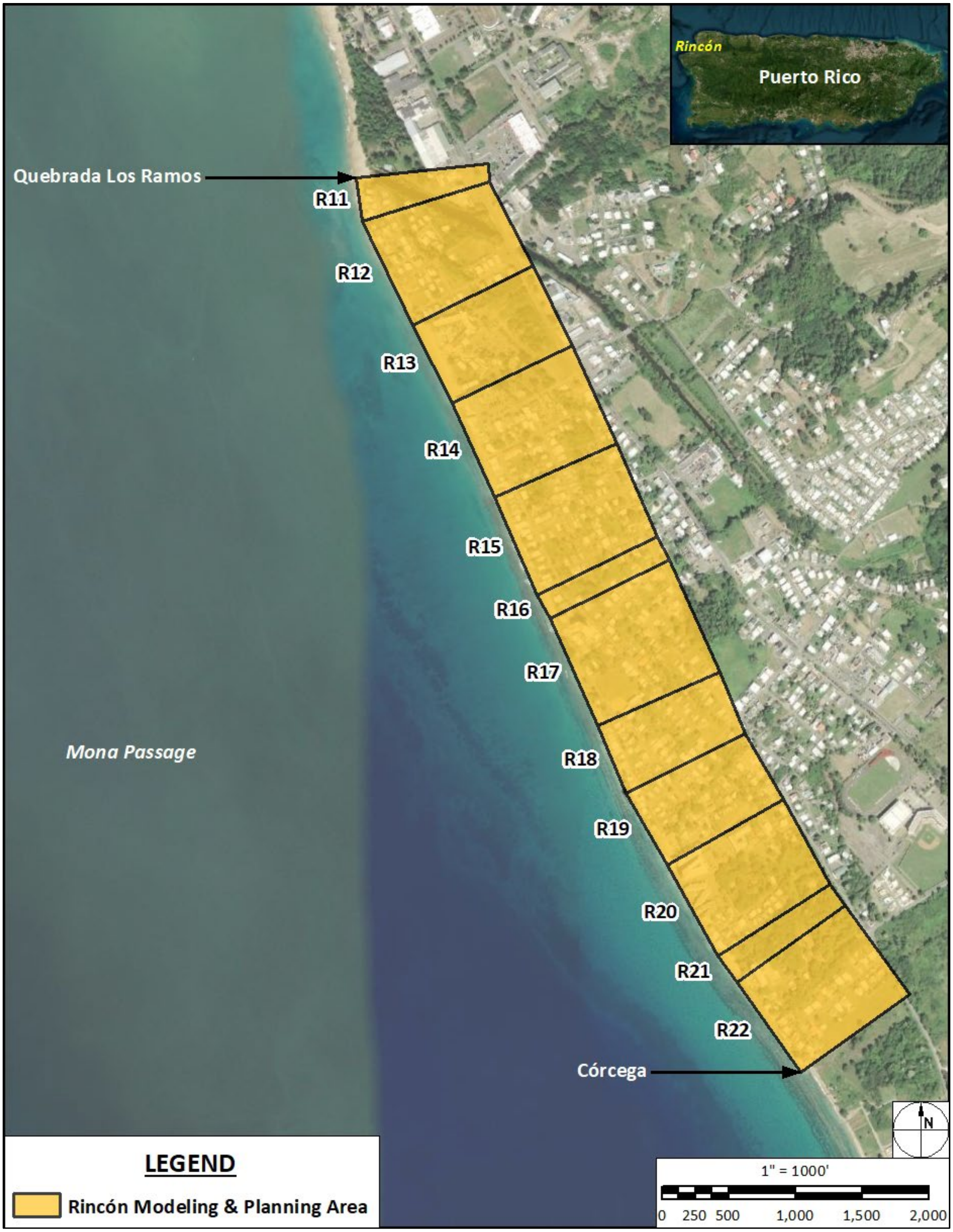


**Figure A-70. Rincón's Modeling and Planning Domains**

## 4.2 Beach-*fx* Input

As previously noted, Beach-*fx* is an event-driven model typically simulated over an economic life cycle of 50 years. The model estimates shoreline response to a series of storm events with defined AEPs. These plausible storms, the damage driving events, are randomly generated using a Monte Carlo type of simulation. Shoreline evolution in Beach-*fx* includes storm-induced beach erosion, typical post-storm beach recovery, and artificial nourishment (either planned or emergency nourishment) throughout the economic life cycle. Risk-based structure damages are estimated based on life cycle storm-induced shoreline responses and pre-determined storm damage functions for every possible structure type within the study area. Uncertainty is incorporated in the input data (storm occurrence and intensity, structural parameters, structure and contents valuations, and damage functions) and applied methodologies (probabilistic seasonal storm generation and multiple iteration life-cycle analysis). Results from many, sometimes hundreds of, life cycle iterations are either averaged or presented as a range of possible values.

Beach-*fx* relies on a combination of engineering and economic inputs and is comprised of four basic elements: meteorological forcing, coastal morphology, economic evaluation, and management measures. There are two Beach-*fx* input databases, the Input Database (IDB) and the Shore Response Database (SDB), that rely on the four basic elements for proper simulation. A third and final database, the Output Database (ODB), yields a massive conglomerate matrix that comprises relevant engineering and economic data that are output by iterative life cycle damage calculations throughout the simulation. The subsequent discussion in this section addresses the basic aspects in Beach-*fx* for the San Juan and Rincón environments. For a more detailed description of Beach-*fx* theory, assumptions, data input/output, and model application, refer to Rogers et al. (2009), Gravens et al. (2010), and USACE (in preparation).

### *4.2.1 Meteorological Forcing*

Storm systems are the main driving mechanisms to morphology changes and structure damages, and these events are broken down into local storm parameters for cross-shore change quantification in Beach-*fx* modeling. The storm parameters needed to complete CSRM study modeling includes wave height, wave period, and SWE. Time series of these data must include peak storm impacts that coincide with a randomized tide phase and amplitude. These parameters are simulated with a cross-shore change model (in this case, Storm-induced BEAch Change or SBEACH) to define the Beach-*fx* SDB. However, storm parameters and intensities should be chosen such that a project shoreline experiences a wide range of possible storm outcomes.

Section 2.1 described the general storm climate for San Juan and Rincón using data from sources like NOAA's water level gauges and USACE's WIS hindcast database. However, the three sources best suited specifically for modeling tasks in this study were as follows: USACE's CHS (hurricanes) and NOAA's NDBC (nor'easters) were used to create the plausible storm suites (Sections 4.2.1.1 through 4.2.1.2) and NOAA's Revised Atlantic Hurricane Data's 2nd Generation (HURDAT2; NOAA, 2021b) database was used to estimate the storm rates of occurrence by yearly season (Section 4.2.1.4). These sources are great publicly available data repositories that are easy to use for CSRM modeling storm suite creation. The CHS is a coastal storm hazards data repository and mining system offering easy access to high fidelity numerical modeling and observed storm responses in a statistical context, but these data only include plausible hurricane data for Puerto Rico. Thus, this study supplemented the nor'easter data deficiency in CHS with NOAA's NDBC records. NDBC stations around the coast of Puerto Rico include decade-long historical meteorological data hosted and maintained by the CarICOOS System. Finally, NOAA's HURDAT2 database includes Atlantic Basin storm data as early as 1851 from the Hurricane Database Re-Analysis Project within

NOAA's Hurricane Research Division that are easily mined using different sampling methods for a project site.

Notably, normal Beach-*fx* studies include combining a wide range of tides with all storm event's peak surge occurrence. Most Beach-*fx* reference documents recommend 12 tide possibilities: high tide, mean tide falling, low tide, and mean tide rising for the lower quartile, mean, and upper quartile tidal ranges. Since Puerto Rico's tidal range is relatively small, only three tide possibilities were considered to minimize model run times: the lower quartile, mean, and upper quartile range with the high tide phase. Hurricanes of short duration and nor'easters potentially lasting days, multiple tides, were combined with tides differently. Each hurricane selected for each project site was combined with all three tides, whereas each nor'easter selected for each project site was combined with the upper quartile high tide. Considering these data in conjunction with tide combinations resulted in a total of 55 events for San Juan (16 hurricanes over three tides each and seven nor'easters) and 73 events for Rincón (22 Hurricanes over three tides each and seven nor'easters). The following sections detail how storms were selected for a given project area, storm relative probabilities, and the storm rates of occurrence by season per year.

#### 4.2.1.1 Hurricane Selection Process

As mentioned above, CHS data along with the South Atlantic Coastal Study's (SACS) Puerto Rico Appendix (USACE, 2022e) were used to develop the hurricane portion of the Beach-*fx* storm suites. The SACS simulated the full set of CHS storms around Puerto Rico using a joint probability optimal sampling routine to define 300 plausible storms with records at save points around the island. This Puerto Rico Coastal Study further sampled 16 hurricanes in the San Juan area and 22 hurricanes in the Rincón area to define a reduced storm suite (RSS) for Beach-*fx*. The number of storms to be selected leveraged knowledge gathered from other previous and ongoing efforts regarding the minimum number of storms required to adequately capture the storm surge hazard. The best outcome is an optimal combination of storms given a predetermined number of hurricanes sampled, referred to as an RSS. In the process of selecting hurricanes, it was determined that an RSS of 16 hurricanes in the San Juan area and 22 hurricanes in the Rincón adequately captured the storm surge hazard for the range of probabilities covered by the initial hurricane (IH) suite.

The storm selection process was performed using the design of experiments (DoE) approach described in detail in Jia et al. (2015) and, more recently, Taflanidis et al. (2017) and Zhang et al. (2018). The DoE compares SWE hazard curves derived from the RSS to "benchmark" curves corresponding to the full storm suite (FSS) at a given number of save points within the study area. The difference between the RSS hazard curves and FSS benchmark curves is minimized in an iterative process considering multiple subsets of the given number of sampled hurricanes (i.e., 16 for San Juan and 22 for Rincón).

In summary, the general steps in this DoE approach for selecting a subset of storms are as follows:

- Identify a save point critical to a project or study area, where optimization will be performed.
- Develop hazard curves for the IH.
- Select number of storms to be sampled.
- Develop hazard curves for the RSS.
- Choose the range of probabilities for which hazard curves will be compared. RSS versus IH differences can be computed along the entire hazard curve, or by prioritizing a specific segment of the curves, e.g., 5 to 500 years.

- Compute differences between RSS and IH hazard curves.
- Perform an iterative sensitivity analysis to determine the optimal combination of storms constituting the RSS.
- Once the optimal combination of storms is determined, perform an optional analysis to evaluate the benefits of increasing storm subset size; finalize storm selection.

The Puerto Rico Coastal Study used, a metamodel with recursive iterative implementation to select an optimal subsample of the CHS storms. The method is based on Gaussian process regression metamodeling (Taflanidis, et al., 2017; Zhang et al., 2018). In this approach, an initial RSS is recursively obtained in the 300-storm hurricane suite. A metamodel is produced for the chosen save point (14863 for San Juan and 488 for Rincón) based on sampled hurricanes with joint probability method parameters as inputs and ADCIRC storm surge as output. Figure A-71 and Figure A-72 show the selected save points for San Juan and Rincón, respectively. The metamodel is then used to predict the SWE hazard curves for the save point location. The metamodel of each sample surrogate is trained and hazard curves are produced at the save point locations. The best storm sample is determined by minimizing the error across the parameter space using a genetic algorithm where the error is reduced between the sample and the full 300 storm set. Many permutations of sampled events are fit and observed using a Monte Carlo selection process of the entire parameter space. This process is repeated until an optimal 16- and 22-event sample is defined for San Juan and Rincón, respectively, that minimizes the error between the target (IH) hazard curve and the sample (RSS).


**Figure A-71. CHS Save Points near the San Juan Study Area (Station 14863 Circled in Red)**

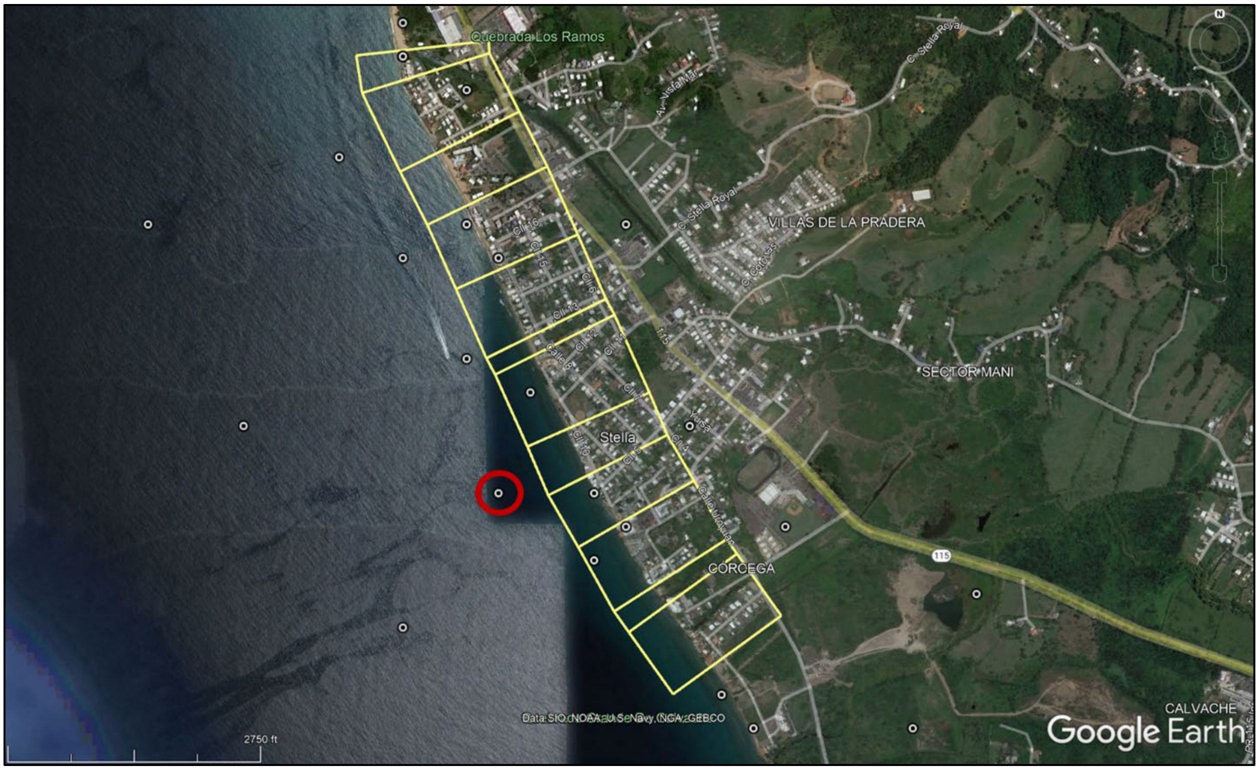


**Figure A-72. CHS Save Points near the Rincón Study Area (Station 488 Circled in Red)**

Figure A-73 and Figure A-74 show an example what the final selection process yields (Rincón depicted). Figure A-73 displays an example of the optimization results in Rincón for the RSS considering the probability of storm occurrence as a means of matching the reduced suite to the "benchmark" or FSS hazard curve (blue). This plot illustrates that a sample of 22 storms converge and ultimately result in a hazard-curve error very close to zero for the intended range of AEPs of the full storm set (i.e., 1 to $10^{-5}$). Figure A-74 depicts the tracks for the RSS storms in Rincón.

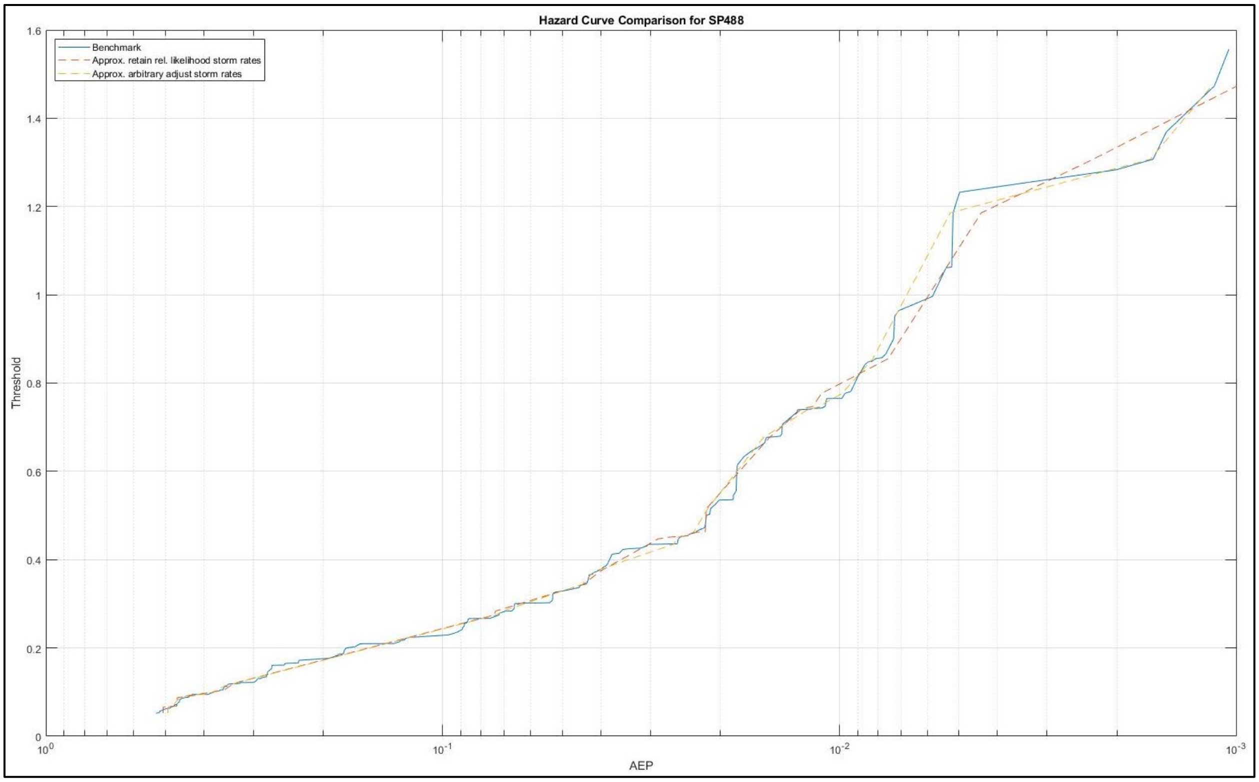


**Figure A-73. Storm Selection Optimization**

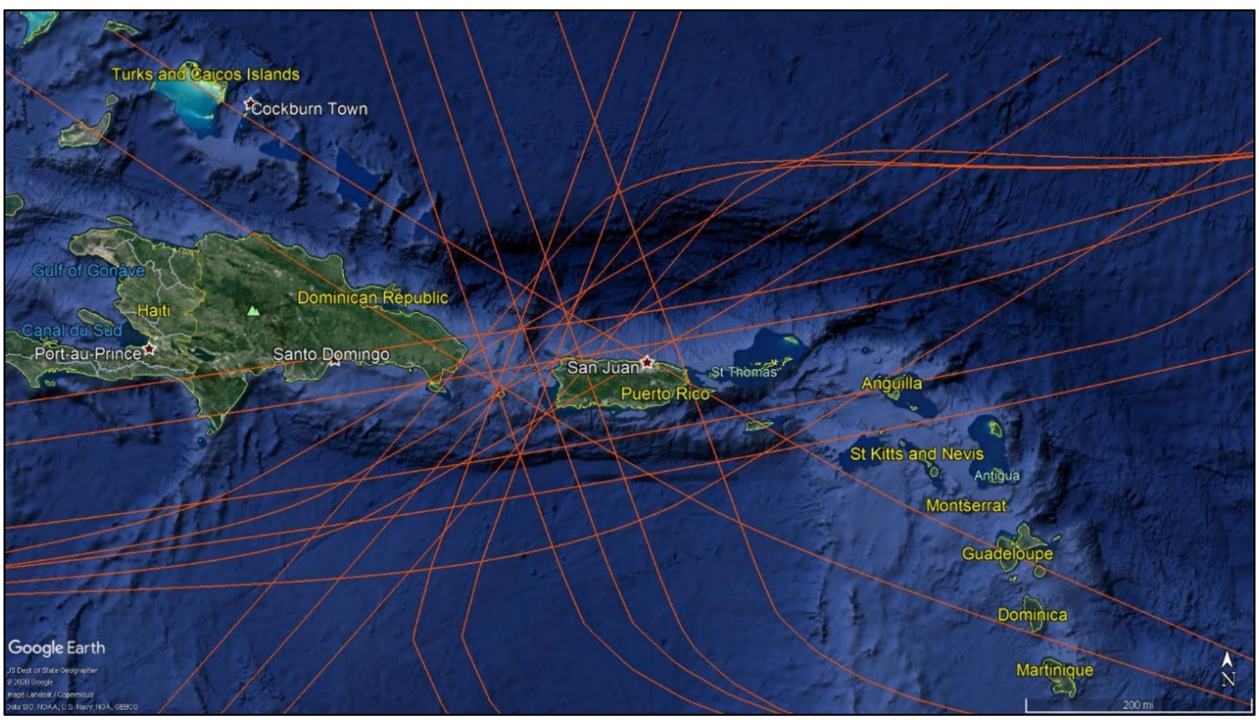


**Figure A-74. Final Selected Hurricane Tracks**

For San Juan, the 16-hurricane dataset at save point 14863 was recorded in 27.30 feet of water. It covers the ~0.2 to ~0.004 AEP, which correspond to 1.15 to 5.25 feet PRVD02 SWEs and 5.15 to 8.39 feet wave heights. For Rincón, the 22-hurricane dataset at save point 488 was recorded in approximately 27.89 feet of water. It covers the ~0.2 to ~0.005 AEP, which correspond to 0.69 to 2.40 feet PRVD02 SWEs and 4.83 to 16.08 feet wave heights. USACE assigned each hurricane an appropriate probability mass from CHS, then modulated to reflect three statistically defined tide ranges (high, medium, and low amplitude) at the highest surge-tide phase. The three tidal ranges and one phase shift result in three plausible total water elevation time series for a single representative hurricane, resulting in a total of 48 possible hurricane combinations in San Juan and 66 possible hurricane combinations in Rincón. Figure A-75 displays an example of a selected hurricane's input parameters for Beach-*fx* modeling that is combined with three tide cycles.

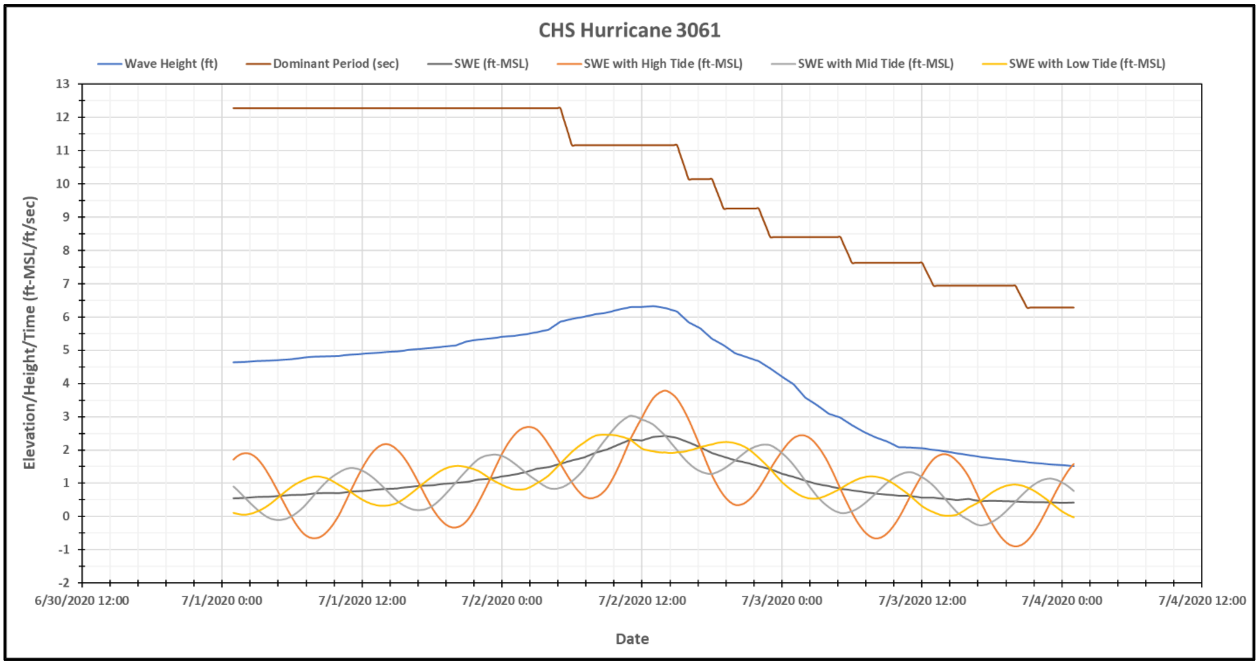


**Figure A-75. Example of a Selected Hurricane Combined with Tides for Beach-*fx* Modeling**

### 4.2.1.2 Nor'easter Selection Process

As mentioned previously, CHS data do not include nor'easters for Puerto Rico. Thus, NDBC stations were used to supplement this data deficiency. The NDBC stations closest to each study area (NDBC Station 41053 for San Juan in Figure A-76 and NDBC Station 41115 for Rincón in Figure A-77) contained raw wave data necessary for nor'easter data sampling. A declustering routine filtered raw wave data peaks that may represent the same storm in the raw data time series, where 15 days represented the time between peak significant wave heights in the raw dataset. Then, a peak-over-threshold routine screened raw wave data that was too low in magnitude to damage the study area, where 5 feet represented the final screening metric on the declustered wave data (Figure A-78). A total of 73 and 72 nor'easters resulted from the analysis in San Juan and Rincón, respectively, and important historical nor'easters such as Winter Storm Riley were intentionally selected for final storm suite inclusion. It is important to note, that the selection process discarded westerly events from the NDBC Station 41115's dataset since the Rincón project site is not exposed to westerly waves.


**Figure A-76. NDBC Station 41053 near San Juan**


**Figure A-77. NDBC Station 41115 near Rincón**

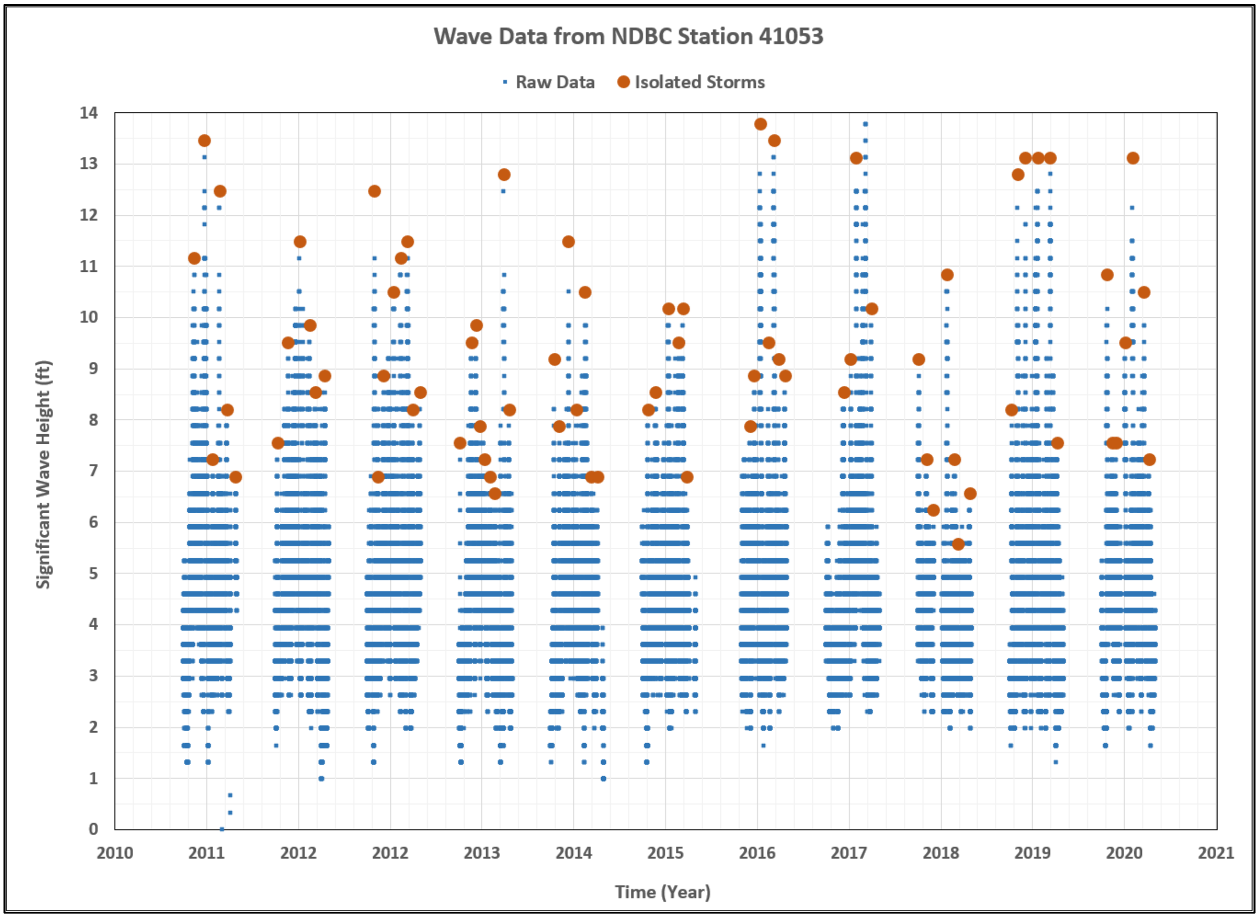


**Figure A-78. Example of Sampling Nor'easter Storm Rates (Declustered Peak-Over-Threshold)**

Following the thinning and declustering of the raw nor'easter data, USACE binned these data for final selection. Peak wave height bins were evenly segregated in two-foot increments starting at 7.0 ft and maxing out at 17 ft. The one nor'easter over 17.0 ft that was selected for both project sites was Winter Storm Riley. Table A-16 and Table A-17 detail the final selected nor'easter by bin for San Juan and Rincón, respectively. After selection of the seven nor'easters for each project site, the selection process combined wave height, wave period, and water level data for the event with a maximum high tide. An example of the resulting nor'easter parameters that were simulated in this study's cross-shore change and Beach-*fx* models is shown in Figure A-79.

**Table A-16. San Juan's Final Nor'easter Binning and Selection (NDBC Station 41053)**

| Bin Start | Bin End | Nor'easters | Selected |
|---|---|---|---|
| < 7.0 | 7.0 | 9 | 2 |
| 7.0 | 9.0 | 27 | 1 |
| 9.0 | 11.0 | 19 | 1 |
| 11.0 | 13.0 | 9 | 1 |
| 13.0 | 15.0 | 8 | 1 |
| 15.0 | 17.0 | 0 | 0 |
| 17.0 | > 17.0 | 1 | 1 |
| **Total Storms:** | | **73** | **7** |

**Table A-17. Rincón's Final Nor'easter Binning and Selection (NDBC Station 4115)**

| Bin Start | Bin End | Nor'easters | Selected |
|---|---|---|---|
| < 7.0 | 7.0 | 20 | 1 |
| 7.0 | 9.0 | 33 | 1 |
| 9.0 | 11.0 | 11 | 1 |
| 11.0 | 13.0 | 5 | 1 |
| 13.0 | 15.0 | 1 | 1 |
| 15.0 | 17.0 | 1 | 1 |
| 17.0 | > 17.0 | 1 | 1 |
| **Total:** | | **72** | **7** |

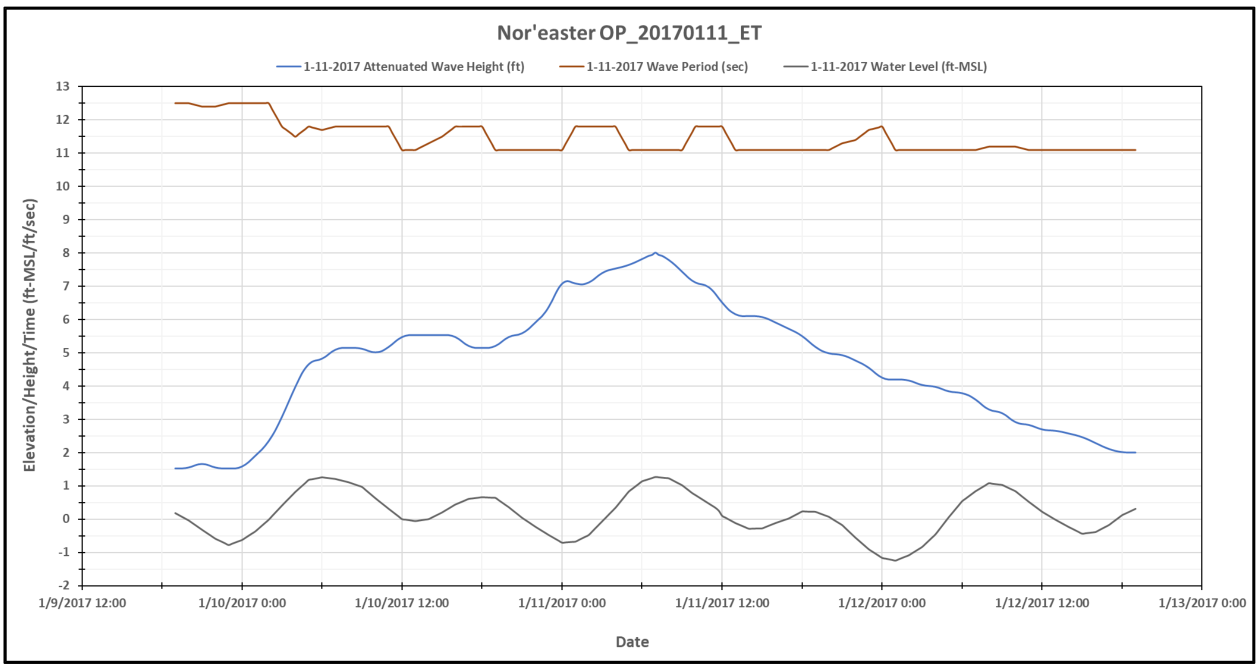


**Figure A-79. Example of a Selected Nor'easter for Beach-*fx* Modeling**

#### 4.2.1.2.1 *Attenuating (Transforming) Nor'easter Wave Energy*

As stated in Section 2.1.3, coastal features in Puerto Rico naturally attenuate incoming wave energy. This means nor'easters selected from offshore NDBC buoys may contain wave energy that is biased high. For San Juan, raw wave data collected by Torruella (2015) inside and outside the fringing reef with AWAC ADP gauges were used to transform NDBC wave data from the offshore buoy depth to the same depth as the San Juan CHS save point (ID 14863). For Rincón, USACE transformed waves linearly since synonymous offshore/inshore raw wave data existed for the area.

The AWAC ADP gauges in San Juan, briefly mentioned in Section 2.1.3.1.1 and shown in Figure A-41, collected raw wave data inside and outside San Juan's fringing reef over a synonymous three week period from 07 February 2015 to 28 February 2015. Four notable nor'easter events impacted the area over this time, which are indicated in Figure A-80. The AWAC buoys were stationed in similar depths as NDBC Station 41053 (outside the fringing reef) and CHS Save Point 14863 (inside the fringing reef). Thus, the AWAC data provided a reliable way to transform offshore NDBC waves to waves that may be present for the same event inside the fringing reef at a depth synonymous to the CHS save point. USACE compared the four events collected by the AWAC gauges over the three-week period to obtain a fringing reef attenuation percentage and applied the attenuation percentage to NDBC Station 41053 nor'easter wave data. The average attenuation percentage over this time equated to 58.14%. Thus, nor'easters in the final San Juan storm suite contained wave heights that were 58.14% smaller than the raw NDBC recorded wave heights.

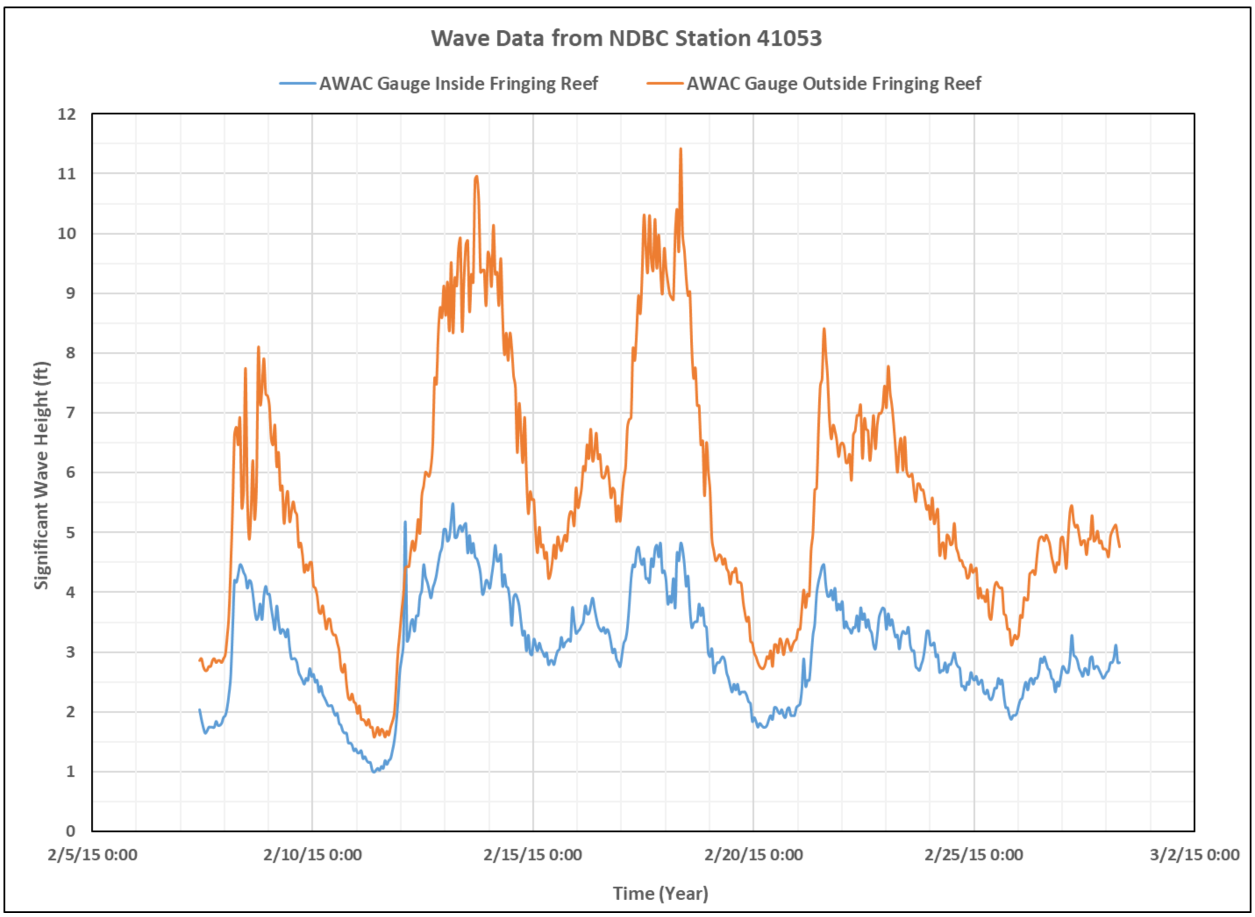


**Figure A-80. AWAC Gauge Comparison for Attenuation Percentage**

#### 4.2.1.3 Final Storm Suites and Associated Probabilities Compiled for Beach-*fx* Modeling

Once USACE sampled and combined all hurricanes and nor'easters with tides, they were ready to be compiled into a final storm suite for each project area. CHS provided hurricane probability masses, and tides that were combined with hurricanes were given a hurricane tide probability of 0.25 for low and high and 0.5 for mid tide. USACE then computed relative probabilities for hurricane-tide combination events by multiplying the hurricane probability mass by the tide probability. Nor'easters that originated from NDBC data were given a probability mass based on how many storms were selected from a given bin. For example, nor'easter Ri_20170102ET3 was sampled from the '< 7.0 ft' bin in Table A-17. Since that nor'easter was selected from a bin that included 20 nor'easters in the 72-nor'easter dataset, the nor'easter probability mass for that storm would equate to 0.2778 (i.e., 20/72=0.277778). Nor'easters were simulated over one tide, so the nor'easter tide probability was equal to 1. Thus, the nor'easter probability mass equates to the combined nor'easter-tide relative probability. It is important to note that relative probabilities in Beach-*fx* must be separated by storm type. This means adding or removing hurricanes to a storm suite has no weight or impact on the relative probabilities for nor'easters, and vice versa.

Table A-18 and Table A-19 list the final storm suite details, where a total of 55 and 73 storms were simulated in San Jaun and Rincón, respectively. The SWE, tide, and wave heights listed in these tables are the maximum values for each storm at the offshore cross-shore change model (SBEACH) boundary, which is at the CHS save point depth for each project site. These time series of each of these storms are simulated in SBEACH and passed to Beach-*fx* for Monte Carlo, life-cycle iterative modeling at the coastline.

**Table A-18. San Juan's Final Storm Suite and Associated Probabilities**

| Storm ID | Storm Type | SWE (ft-PRVD02) | Tide (ft-PRVD02) | Wave Height (ft) | Relative Probability |
|---|---|---|---|---|---|
| OP_19220917_3164_H | Hurricane | 1.5 | 1.3 | 6.2 | 0.027759 |
| OP_19220917_3164_M | Hurricane | 1.5 | 0.7 | 6.2 | 0.055517 |
| OP_19220917_3164_L | Hurricane | 1.5 | 0.5 | 6.2 | 0.027759 |
| OP_19280913_3129_H | Hurricane | 1.7 | 1.3 | 6.1 | 0.006191 |
| OP_19280913_3129_M | Hurricane | 1.7 | 0.7 | 6.1 | 0.012382 |
| OP_19280913_3129_L | Hurricane | 1.7 | 0.5 | 6.1 | 0.006191 |
| OP_19310911_3046_H | Hurricane | 1.6 | 1.3 | 6.0 | 0.007010 |
| OP_19310911_3046_M | Hurricane | 1.6 | 0.7 | 6.0 | 0.014020 |
| OP_19310911_3046_L | Hurricane | 1.6 | 0.5 | 6.0 | 0.007010 |
| OP_19320927_3023_H | Hurricane | 1.7 | 1.3 | 5.3 | 0.006850 |
| OP_19320927_3023_M | Hurricane | 1.7 | 0.7 | 5.3 | 0.013700 |
| OP_19320927_3023_L | Hurricane | 1.7 | 0.5 | 5.3 | 0.006850 |
| OP_19500902_3072_H | Hurricane | 3.7 | 1.3 | 7.9 | 0.027739 |
| OP_19500902_3072_M | Hurricane | 3.7 | 0.7 | 7.9 | 0.055478 |
| OP_19500902_3072_L | Hurricane | 3.7 | 0.5 | 7.9 | 0.027739 |
| OP_19550807_3074_H | Hurricane | 3.8 | 1.3 | 7.5 | 0.005739 |
| OP_19550807_3074_M | Hurricane | 3.8 | 0.7 | 7.5 | 0.011477 |
| OP_19550807_3074_L | Hurricane | 3.8 | 0.5 | 7.5 | 0.005739 |

| Storm ID | Storm Type | SWE (ft-PRVD02) | Tide (ft-PRVD02) | Wave Height (ft) | Relative Probability |
|---|---|---|---|---|---|
| OP_19560812_3004_H | Hurricane | 2.1 | 1.3 | 5.9 | 0.002835 |
| OP_19560812_3004_M | Hurricane | 2.1 | 0.7 | 5.9 | 0.005670 |
| OP_19560812_3004_L | Hurricane | 2.1 | 0.5 | 5.9 | 0.002835 |
| OP_19600905_3238_H | Hurricane | 3.7 | 1.3 | 7.6 | 0.000569 |
| OP_19600905_3238_M | Hurricane | 3.7 | 0.7 | 7.6 | 0.001138 |
| OP_19600905_3238_L | Hurricane | 3.7 | 0.5 | 7.6 | 0.000569 |
| OP_19660827_3299_H | Hurricane | 1.2 | 1.3 | 5.7 | 0.004805 |
| OP_19660827_3299_M | Hurricane | 1.2 | 0.7 | 5.7 | 0.009610 |
| OP_19660827_3299_L | Hurricane | 1.2 | 0.5 | 5.7 | 0.004805 |
| OP_19950906_3031_H | Hurricane | 2.0 | 1.3 | 6.2 | 0.003001 |
| OP_19950906_3031_M | Hurricane | 2.0 | 0.7 | 6.2 | 0.006001 |
| OP_19950906_3031_L | Hurricane | 2.0 | 0.5 | 6.2 | 0.003001 |
| OP_19950916_3191_H | Hurricane | 1.8 | 1.3 | 6.0 | 0.000653 |
| OP_19950916_3191_M | Hurricane | 1.8 | 0.7 | 6.0 | 0.001306 |
| OP_19950916_3191_L | Hurricane | 1.8 | 0.5 | 6.0 | 0.000653 |
| OP_19980921_3065_H | Hurricane | 4.5 | 1.3 | 8.4 | 0.000308 |
| OP_19980921_3065_M | Hurricane | 4.5 | 0.7 | 8.4 | 0.000616 |
| OP_19980921_3065_L | Hurricane | 4.5 | 0.5 | 8.4 | 0.000308 |
| OP_20040831_3067_H | Hurricane | 4.7 | 1.3 | 7.9 | 0.003771 |
| OP_20040831_3067_M | Hurricane | 4.7 | 0.7 | 7.9 | 0.007542 |
| OP_20040831_3067_L | Hurricane | 4.7 | 0.5 | 7.9 | 0.003771 |
| OP_20110822_3192_H | Hurricane | 1.6 | 1.3 | 5.8 | 0.000177 |
| OP_20110822_3192_M | Hurricane | 1.6 | 0.7 | 5.8 | 0.000354 |
| OP_20110822_3192_L | Hurricane | 1.6 | 0.5 | 5.8 | 0.000177 |
| OP_20141014_3039_H | Hurricane | 1.7 | 1.3 | 6.0 | 0.017735 |
| OP_20141014_3039_M | Hurricane | 1.7 | 0.7 | 6.0 | 0.035471 |
| OP_20141014_3039_L | Hurricane | 1.7 | 0.5 | 6.0 | 0.017735 |
| OP_20190829_3061_H | Hurricane | 2.4 | 1.3 | 6.3 | 0.000260 |
| OP_20190829_3061_M | Hurricane | 2.4 | 0.7 | 6.3 | 0.000520 |
| OP_20190829_3061_L | Hurricane | 2.4 | 0.5 | 6.3 | 0.000260 |
| 20150405ET1 | Nor'easter | 0.5 | 1.3 | 6.9 | 0.123288 |
| 20161218ET2 | Nor'easter | 0.4 | 1.3 | 8.9 | 0.369863 |
| 20170111ET3 | Nor'easter | 0.6 | 1.3 | 13.8 | 0.109589 |
| 20180305ET4 | Nor'easter | 0.8 | 1.3 | 17.1 | 0.013699 |
| 20190309ET5 | Nor'easter | 0.4 | 1.3 | 5.6 | 0.123288 |
| 20191101ET6 | Nor'easter | 0.7 | 1.3 | 12.8 | 0.123288 |
| 20201022ET7 | Nor'easter | 0.4 | 1.3 | 10.8 | 0.260274 |

**Table A-19. Rincón's Final Storm Suite and Associated Probabilities**

| Storm ID | Storm Type | SWE (ft-PRVD02) | Tide (ft-PRVD02) | Wave Height (ft) | Relative Probability |
|---|---|---|---|---|---|
| TS-3004_TAmp_1 | Hurricane | 2.0 | 0.4 | 15.1 | 0.000407 |
| TS-3004_TAmp_2 | Hurricane | 2.0 | 0.6 | 15.1 | 0.000814 |
| TS-3004_TAmp_3 | Hurricane | 2.0 | 0.9 | 15.1 | 0.000407 |
| TS-3009_TAmp_1 | Hurricane | 2.4 | 0.4 | 14.8 | 0.000005 |
| TS-3009_TAmp_2 | Hurricane | 2.4 | 0.6 | 14.8 | 0.000010 |
| TS-3009_TAmp_3 | Hurricane | 2.4 | 0.9 | 14.8 | 0.000005 |
| TS-3015_TAmp_1 | Hurricane | 0.9 | 0.4 | 13.5 | 0.010177 |
| TS-3015_TAmp_2 | Hurricane | 0.9 | 0.6 | 13.5 | 0.020353 |
| TS-3015_TAmp_3 | Hurricane | 0.9 | 0.9 | 13.5 | 0.010177 |
| TS-3051_TAmp_1 | Hurricane | 2.5 | 0.4 | 15.3 | 0.003334 |
| TS-3051_TAmp_2 | Hurricane | 2.5 | 0.6 | 15.3 | 0.006668 |
| TS-3051_TAmp_3 | Hurricane | 2.5 | 0.9 | 15.3 | 0.003334 |
| TS-3062_TAmp_1 | Hurricane | 0.7 | 0.4 | 4.8 | 0.015229 |
| TS-3062_TAmp_2 | Hurricane | 0.7 | 0.6 | 4.8 | 0.030459 |
| TS-3062_TAmp_3 | Hurricane | 0.7 | 0.9 | 4.8 | 0.015229 |
| TS-3074_TAmp_1 | Hurricane | 1.5 | 0.4 | 9.7 | 0.001144 |
| TS-3074_TAmp_2 | Hurricane | 1.5 | 0.6 | 9.7 | 0.002288 |
| TS-3074_TAmp_3 | Hurricane | 1.5 | 0.9 | 9.7 | 0.001144 |
| TS-3097_TAmp_1 | Hurricane | 0.5 | 0.4 | 7.6 | 0.001098 |
| TS-3097_TAmp_2 | Hurricane | 0.5 | 0.6 | 7.6 | 0.002197 |
| TS-3097_TAmp_3 | Hurricane | 0.5 | 0.9 | 7.6 | 0.001098 |
| TS-3098_TAmp_1 | Hurricane | 0.7 | 0.4 | 7.1 | 0.015323 |
| TS-3098_TAmp_2 | Hurricane | 0.7 | 0.6 | 7.1 | 0.030645 |
| TS-3098_TAmp_3 | Hurricane | 0.7 | 0.9 | 7.1 | 0.015323 |
| TS-3111_TAmp_1 | Hurricane | 0.9 | 0.4 | 13.3 | 0.010920 |
| TS-3111_TAmp_2 | Hurricane | 0.9 | 0.6 | 13.3 | 0.021841 |
| TS-3111_TAmp_3 | Hurricane | 0.9 | 0.9 | 13.3 | 0.010920 |
| TS-3139_TAmp_1 | Hurricane | 0.8 | 0.4 | 14.3 | 0.004628 |
| TS-3139_TAmp_2 | Hurricane | 0.8 | 0.6 | 14.3 | 0.009256 |
| TS-3139_TAmp_3 | Hurricane | 0.8 | 0.9 | 14.3 | 0.004628 |
| TS-3144_TAmp_1 | Hurricane | 0.8 | 0.4 | 11.9 | 0.008871 |
| TS-3144_TAmp_2 | Hurricane | 0.8 | 0.6 | 11.9 | 0.017743 |
| TS-3144_TAmp_3 | Hurricane | 0.8 | 0.9 | 11.9 | 0.008871 |
| TS-3150_TAmp_1 | Hurricane | 2.0 | 0.4 | 13.7 | 0.003039 |
| TS-3150_TAmp_2 | Hurricane | 2.0 | 0.6 | 13.7 | 0.006078 |
| TS-3150_TAmp_3 | Hurricane | 2.0 | 0.9 | 13.7 | 0.003039 |
| TS-3153_TAmp_1 | Hurricane | 1.4 | 0.4 | 12.7 | 0.009307 |
| TS-3153_TAmp_2 | Hurricane | 1.4 | 0.6 | 12.7 | 0.018614 |

| Storm ID | Storm Type | SWE (ft-PRVD02) | Tide (ft-PRVD02) | Wave Height (ft) | Relative Probability |
|---|---|---|---|---|---|
| TS-3153_TAmp_3 | Hurricane | 1.4 | 0.9 | 12.7 | 0.009307 |
| TS-3156_TAmp_1 | Hurricane | 1.7 | 0.4 | 13.7 | 0.002286 |
| TS-3156_TAmp_2 | Hurricane | 1.7 | 0.6 | 13.7 | 0.004571 |
| TS-3156_TAmp_3 | Hurricane | 1.7 | 0.9 | 13.7 | 0.002286 |
| TS-3168_TAmp_1 | Hurricane | 1.2 | 0.4 | 13.9 | 0.002865 |
| TS-3168_TAmp_2 | Hurricane | 1.2 | 0.6 | 13.9 | 0.005729 |
| TS-3168_TAmp_3 | Hurricane | 1.2 | 0.9 | 13.9 | 0.002865 |
| TS-3198_TAmp_1 | Hurricane | 0.8 | 0.4 | 14.5 | 0.002903 |
| TS-3198_TAmp_2 | Hurricane | 0.8 | 0.6 | 14.5 | 0.005806 |
| TS-3198_TAmp_3 | Hurricane | 0.8 | 0.9 | 14.5 | 0.002903 |
| TS-3201_TAmp_1 | Hurricane | 0.3 | 0.4 | 11.4 | 0.004288 |
| TS-3201_TAmp_2 | Hurricane | 0.3 | 0.6 | 11.4 | 0.008576 |
| TS-3201_TAmp_3 | Hurricane | 0.3 | 0.9 | 11.4 | 0.004288 |
| TS-3205_TAmp_1 | Hurricane | 3.9 | 0.4 | 14.6 | 0.000723 |
| TS-3205_TAmp_2 | Hurricane | 3.9 | 0.6 | 14.6 | 0.001445 |
| TS-3205_TAmp_3 | Hurricane | 3.9 | 0.9 | 14.6 | 0.000723 |
| TS-3260_TAmp_1 | Hurricane | 3.3 | 0.4 | 16.1 | 0.000648 |
| TS-3260_TAmp_2 | Hurricane | 3.3 | 0.6 | 16.1 | 0.001297 |
| TS-3260_TAmp_3 | Hurricane | 3.3 | 0.9 | 16.1 | 0.000648 |
| TS-3267_TAmp_1 | Hurricane | 2.4 | 0.4 | 14.6 | 0.002240 |
| TS-3267_TAmp_2 | Hurricane | 2.4 | 0.6 | 14.6 | 0.004480 |
| TS-3267_TAmp_3 | Hurricane | 2.4 | 0.9 | 14.6 | 0.002240 |
| TS-3276_TAmp_1 | Hurricane | 1.8 | 0.4 | 15.6 | 0.000029 |
| TS-3276_TAmp_2 | Hurricane | 1.8 | 0.6 | 15.6 | 0.000058 |
| TS-3276_TAmp_3 | Hurricane | 1.8 | 0.9 | 15.6 | 0.000029 |
| TS-3278_TAmp_1 | Hurricane | 0.7 | 0.4 | 6.8 | 0.009650 |
| TS-3278_TAmp_2 | Hurricane | 0.7 | 0.6 | 6.8 | 0.019301 |
| TS-3278_TAmp_3 | Hurricane | 0.7 | 0.9 | 6.8 | 0.009650 |
| Ri_20160121ET1 | Nor'easter | 0.5 | 0.9 | 10.1 | 0.152778 |
| Ri_20160419ET2 | Nor'easter | 0.5 | 0.9 | 8.1 | 0.458333 |
| Ri_20170102ET3 | Nor'easter | 0.5 | 0.9 | 6.7 | 0.277778 |
| Ri_20170110ET4 | Nor'easter | 0.4 | 0.9 | 15.3 | 0.013889 |
| Ri_20180304ET5 | Nor'easter | 1.7 | 0.9 | 17.5 | 0.013889 |
| Ri_20200119ET6 | Nor'easter | 0.7 | 0.9 | 13.3 | 0.013889 |
| Ri_20210130ET7 | Nor'easter | 0.4 | 0.9 | 12.3 | 0.069444 |

#### 4.2.1.4 Storm Seasons and Occurrence Rates

As discussed in previous sections, two general types of events are in the modeling storm suite for this study: hurricanes and nor’easters. Creating hurricane input for Beach-*fx* modeling was completed by using data from the CHS repository, whereas creating nor'easters for Beach-*fx* used raw NDBC data. All storms in Beach-*fx* require a date stamp, even if the storm is synthetic, so Beach-*fx* can "bin" storms for randomized future selection. Thus, modelers need to define the bins, otherwise known as storm seasons, to properly group storms into applicable selection periods. The storm seasons not only act as a mechanism to group types of hurricanes together for proper model selection, but the storm rates associated with each season/type cumulate to the total number of storms that will be sampled by the model each year (on average).

While synthetic storms in Beach-*fx* used data from CHS and NDBC, NOAA's HURDAT2 database proved a more comprehensive historic database to quantify the rate at which hurricanes impact the study areas. Therefore, the storm rate of occurrence by season was computed from the HURDAT2 database for hurricanes. NOAA's HURDAT2 interactive hurricane tracker website (NOAA, 2021b) makes screening hurricanes for a particular area, threshold, or time range fast and easy. Following Gravens and Sanderson (2018), a 200-kilometer (roughly 125 miles) selection radius centered on San Juan yielded a total of 143 storms that passed through the area from 1851 to 2020 (i.e., 0.84 tropical storms per year). A total of 131 tropical storms passed through the Rincón study area with the same sampling method (i.e., 0.77 tropical storms per year).

The HURDAT2 database includes nor'easters, but sampling nor'easters the same way (using a sample radius) as tropical storms may yield an incomplete nor'easter dataset for a given study area. This is because impacts to a study area may come from nor'easters that are thousands of miles away instead of 200 kilometers away. The same NDBC stations and peak-over-threshold-to-declustering routine detailed in Section 4.2.1.2 were used to estimate the total number of nor'easters per year. A total of 73 and 72 nor'easters resulted from the analysis in San Juan and Rincón, respectively, which yielded 6.90 and 6.80 storms per year for these locations.

Figure A-81 shows an example of the tropical storm sampling via the NOAA HURDAT2 sampling tool on the interactive hurricane tracker website, and Figure A-78 shows how nor'easter storms were declustered and sampled from an NDBC dataset (both for the San Juan study area). Table A-20 and Table A-21 detail the storms per year for both storm types and both study areas. Table A-20 summarizes the final Beach-*fx* storm rates from these data. In total, 7.73 and 7.57 storms impact the San Juan and Rincón study sites on average each year.

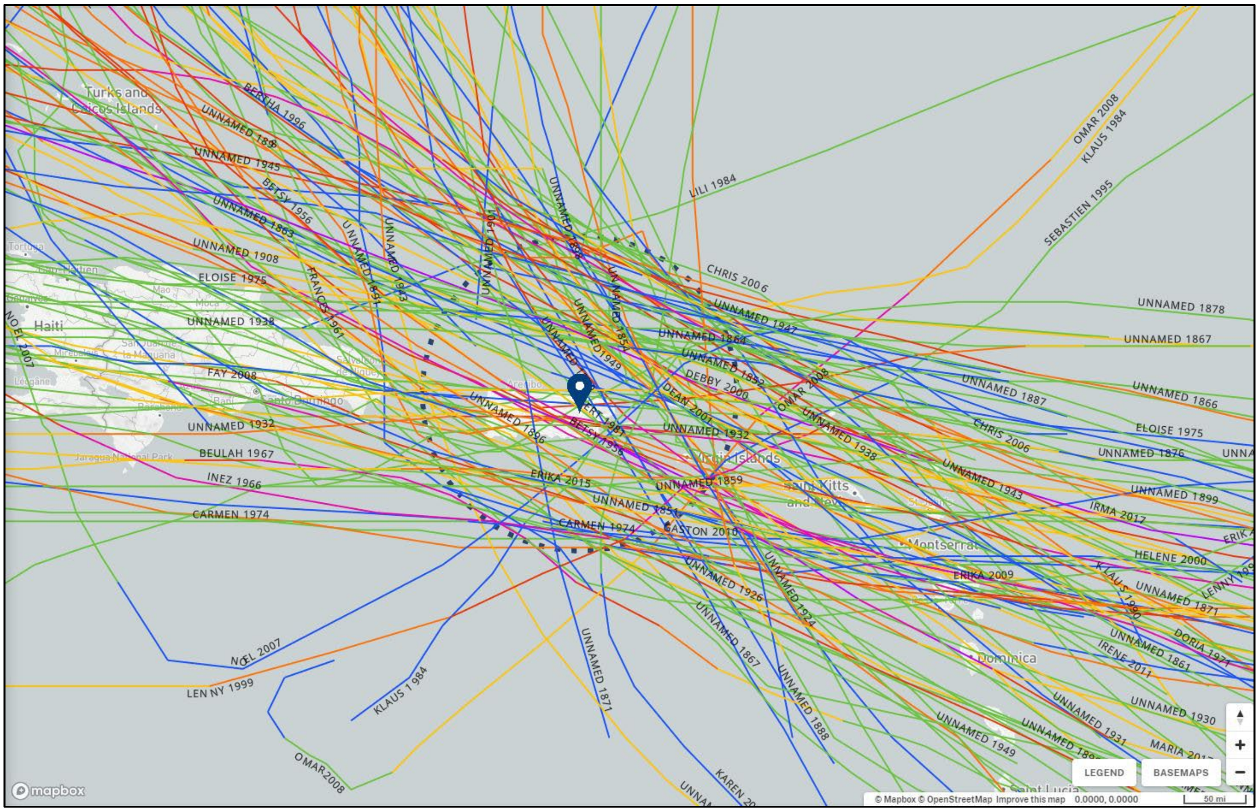


**Figure A-81. Example of Sampling Hurricane Rates from HURDAT2 (NOAA, 2021b)**

**Table A-20. Total Storm Occurrence Rates for San Juan**

| Month of the Year | Tropical Storm Count (NOAA) | Tropical Storm Rate from 1900 to 2020 (NOAA) | Nor'easter Storm Count (NDBC) | Nor'easter Storm Rate from 2010 to 2021 (NDBC) |
|---|---|---|---|---|
| January | 0 | 0.00 | 13 | 1.23 |
| February | 0 | 0.00 | 9 | 0.85 |
| March | 0 | 0.00 | 14 | 1.32 |
| April | 0 | 0.00 | 9 | 0.85 |
| May | 0 | 0.00 | 0 | 0.00 |
| June | 0 | 0.00 | 0 | 0.00 |
| July | 10 | 0.06 | 0 | 0.00 |
| August | 49 | 0.29 | 0 | 0.00 |
| September | 56 | 0.33 | 0 | 0.00 |
| October | 22 | 0.13 | 8 | 0.76 |
| November | 4 | 0.02 | 10 | 0.94 |
| December | 2 | 0.01 | 10 | 0.94 |
| **Total:** | **143** | **0.84** | **73** | **6.90** |

**Table A-21. Total Storm Occurrence Rates for Rincón**

| Month of the Year | Tropical Storm Count (NOAA) | Tropical Storm Rate from 1900 to 2020 (NOAA) | Nor'easter Storm Count (NDBC) | Nor'easter Storm Rate from 2010 to 2021 (NDBC) |
|---|---|---|---|---|
| January | 0 | 0.00 | 19 | 1.79 |
| February | 0 | 0.00 | 17 | 1.61 |
| March | 0 | 0.00 | 14 | 1.32 |
| April | 0 | 0.00 | 8 | 0.76 |
| May | 1 | 0.01 | 1 | 0.09 |
| June | 0 | 0.00 | 0 | 0.00 |
| July | 13 | 0.08 | 0 | 0.00 |
| August | 46 | 0.27 | 0 | 0.00 |
| September | 47 | 0.28 | 0 | 0.00 |
| October | 18 | 0.11 | 0 | 0.00 |
| November | 4 | 0.02 | 0 | 0.00 |
| December | 2 | 0.01 | 13 | 1.23 |
| **Total:** | **131** | **0.77** | **72** | **6.80** |

**Table A-22. Storm Seasons by Study Area for Beach-*fx* Modeling**

| Study Area | Season Range | Season Type | Storm Rate of Occurrence |
|---|---|---|---|
| San Juan (Condado, Ocean Park, and Isla Verde) | 01 May - 31 Oct. | Tropical | 0.84 |
| | 01 Nov. - 30 Apr. | Nor'easter | 6.90 |
| **Total Storms Per Year:** | | | **7.73** |
| Rincón | 01 June - 30 Nov. | Tropical | 0.77 |
| | 01 Dec. - 31 May | Nor'easter | 6.80 |
| **Total Storms Per Year:** | | | **7.57** |

### *4.2.2 Coastal Morphology*

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

- storm-Induced shoreline response from a cross-shore change model
- applied shoreline change rate
- 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.

#### 4.2.2.1 Storm-Induced Shoreline 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 study area; Figure A-82 displays a typical idealized profile. For the Puerto Rico Coastal Study, application of the storm set to the idealized profiles was accomplished with the SBEACH coastal processes response model (Larson and Kraus, 1989). SBEACH 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 SBEACH and imported into the Beach-*fx* Shore Response Database. The Shore Response Database is a relational database used by the Beach-*fx* model to pre-store results of SBEACH simulations of all plausible storms impacting a pre-defined range of anticipated beach profile configurations.

##### *4.2.2.1.1 Idealized Representative Profiles*

To develop the idealized beach profiles, 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. Typically, historical profiles at each Florida Department of Environmental Protection (FDEP) R-monument would be compared over time, aligned, and then averaged into a composite profile representative of the shoreline shape at that given R-monument location. Composite profiles would then be compared and separated into groupings according to the similarity between the below seven dimensions. Within Puerto Rico there is limited historical data to generate these profiles, therefore 2018 LiDAR data was used to create the idealized representative profiles.

- upland elevation
- dune slope
- dune height
- dune width
- berm height
- berm width
- foreshore slope

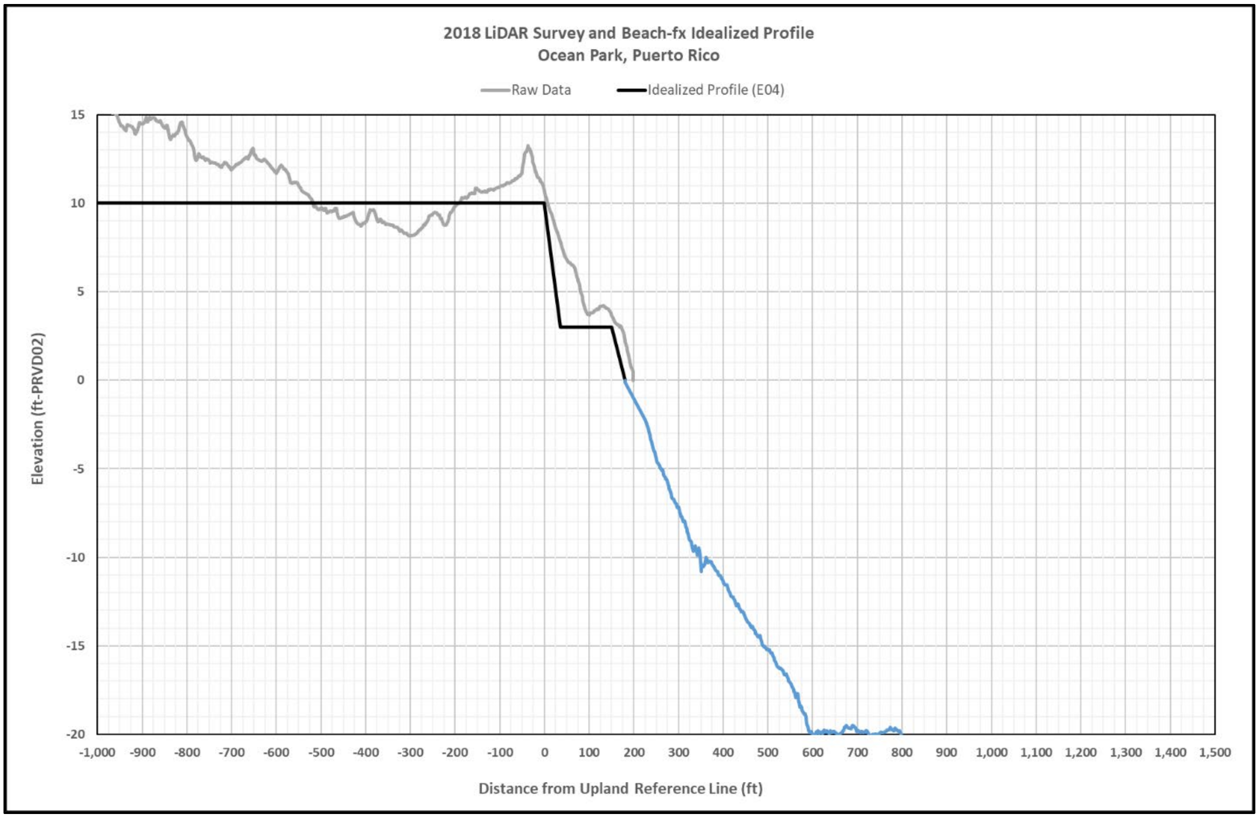


**Figure A-82. Typical Idealized Profile**

#### *4.2.2.1.2 Future Without-Project Profiles*

The base year for the present Puerto Rico Coastal Study is 2029, and the model start year is 2028 (shoreline evolution data, SLC data, etc. were established to 2028). To determine the condition of the project shoreline at the model start year, historical pre-project surveys were studied. USACE took the most recent survey (prior to initiation of this study) in 2018 and was the closest representation of 2028 shoreline. Table A-23 to Table A-26 provides dimensions for each of the idealized pre-storm Beach-*fx* profiles in Condado, Ocean Park, Isla Verde, and Rincón, respectively. Figure A-83 to Figure A-86 display the accompanying cross-shore profile locations by model reach.

**Table A-23. Idealized FWOP Profiles for the Beach-*fx* Condado Model**

| Profile | Model Reach | Upland Elevation (ft PRV02) | Dune Elevation (ft PRV02) | Dune Width (ft) | Berm Elevation (ft PRV02) | Berm Width (ft) |
|---|---|---|---|---|---|---|
| CO01 | R01 | 10 | 10 | 0 | 3 | 80 |
| CO02 | R02 | 11 | 11 | 0 | 3 | 90 |
| CO03 | R03 | 16 | 16 | 0 | 3 | 100 |
| CO04 | R04 | 13 | 13 | 0 | 3 | 90 |
| CO05 | R05-R06 | 14 | 14 | 0 | 3 | 65 |
| CO06 | R07 | 15 | 15 | 0 | 3 | 30 |
| CO07 | R08 | 15 | 15 | 0 | 3 | 0 |
| CO08 | R09 | 13 | 13 | 0 | 3 | 0 |

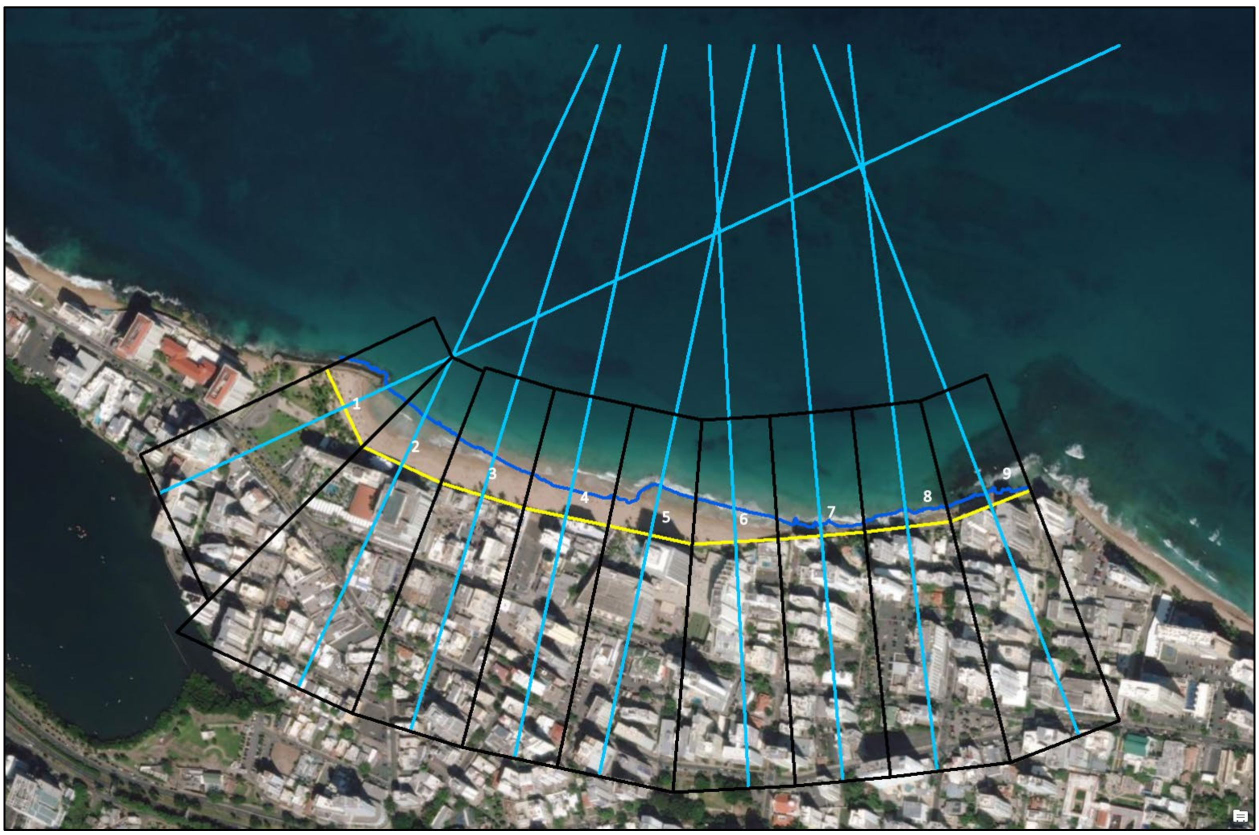


**Figure A-83. Beach-*fx* Condado Model Area and Profile Locations**

**Table A-24. Idealized FWOP Profiles for the Beach-*fx* Ocean Park Model**

| Profile | Model Reach | Upland Elevation (ft PRV02) | Dune Elevation (ft PRV02) | Dune Width* (ft) | Berm Elevation (ft PRV02) | Berm Width (ft) |
|---|---|---|---|---|---|---|
| B*fx*01 | E01 | 9 | 9 | 0 | 3 | 10 |
| B*fx*02 | E02-E03 | 9 | 9 | 0 | 3 | 70 |
| B*fx*03 | E04 | 10 | 10 | 0 | 3 | 115 |
| B*fx*04 | E05-E06 | 10 | 10 | 0 | 3 | 170 |
| B*fx*05 | E07-E08 | 8 | 8 | 0 | 3 | 190 |
| B*fx*06 | E09 | 6 | 6 | 0 | 3 | 150 |
| B*fx*07 | E10 | 5 | 5 | 0 | 3 | 90 |
| B*fx*08 | E11 | 4 | 4 | 0 | 3 | 50 |
| B*fx*09 | E12 | 4 | 4 | 0 | 3 | 20 |
| B*fx*10 | E13 | 4 | 4 | 0 | 3 | 0 |
| B*fx*11 | E14-E21 | 5 | 5 | 0 | 3 | 0 |
| B*fx*12 | E22 | 6 | 6 | 0 | 3 | 0 |

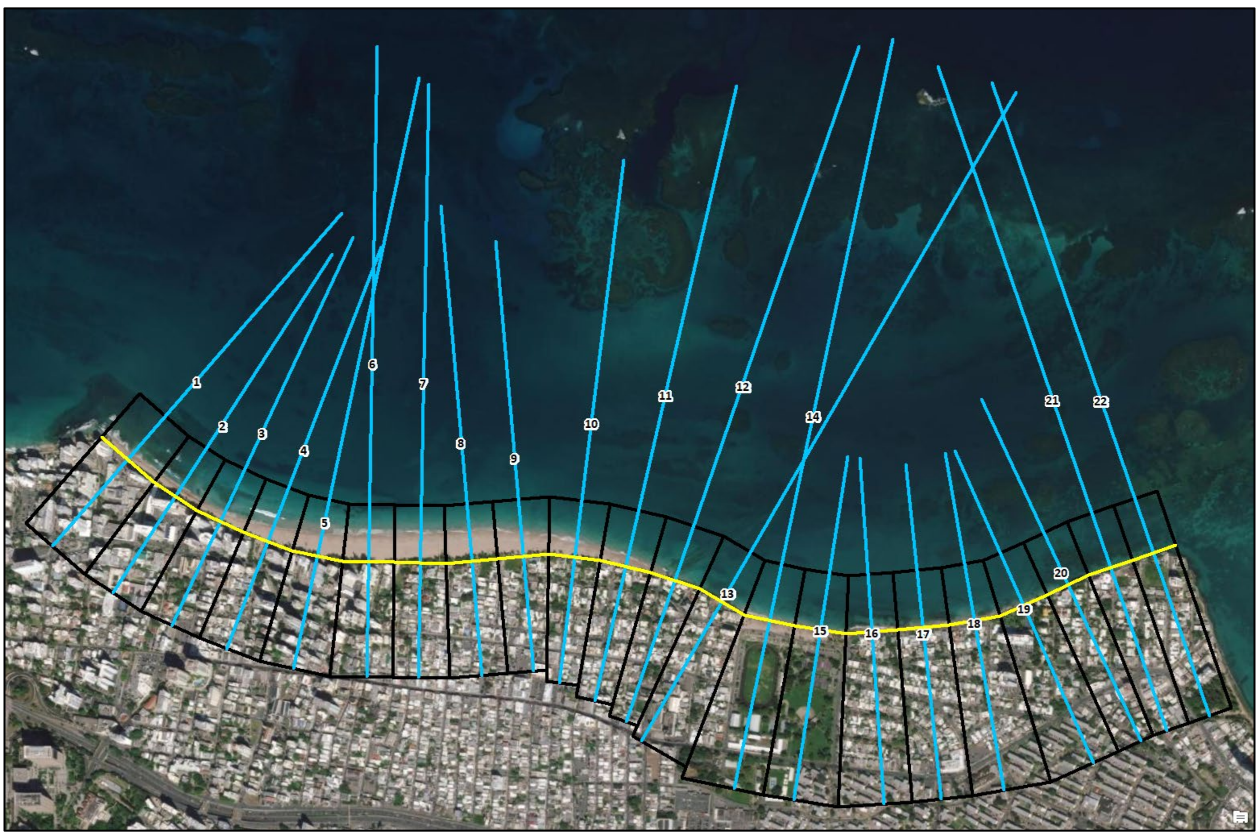


**Figure A-84. Beach-*fx* Ocean Park Model Area and Profile Locations**

**Table A-25. Idealized FWOP Profiles for the Beach-*fx* Isla Verde Model**

| Profile | Model Reach | Upland Elevation (ft PRV02) | Dune Elevation (ft PRV02) | Dune Width* (ft) | Berm Elevation (ft PRV02) | Berm Width (ft) |
|---|---|---|---|---|---|---|
| IV1 | R01 | 7 | 7 | 20 | 3 | 0 |
| IV2 | R02-R03 | 8 | 8 | 20 | 3 | 0 |
| IV3 | R04-R05, R09 | 8 | 8 | 20 | 3 | 0 |
| IV4 | R06-R07 | 9 | 9 | 20 | 3 | 0 |
| IV5 | R08, R10-R11 | 9 | 9 | 20 | 3 | 0 |
| IV6 | R12-R13 | 8 | 8 | 20 | 3 | 0 |
| IV7 | R14 | 6 | 6 | 20 | 3 | 0 |
| IV8 | R15 | 6 | 6 | 20 | 3 | 0 |

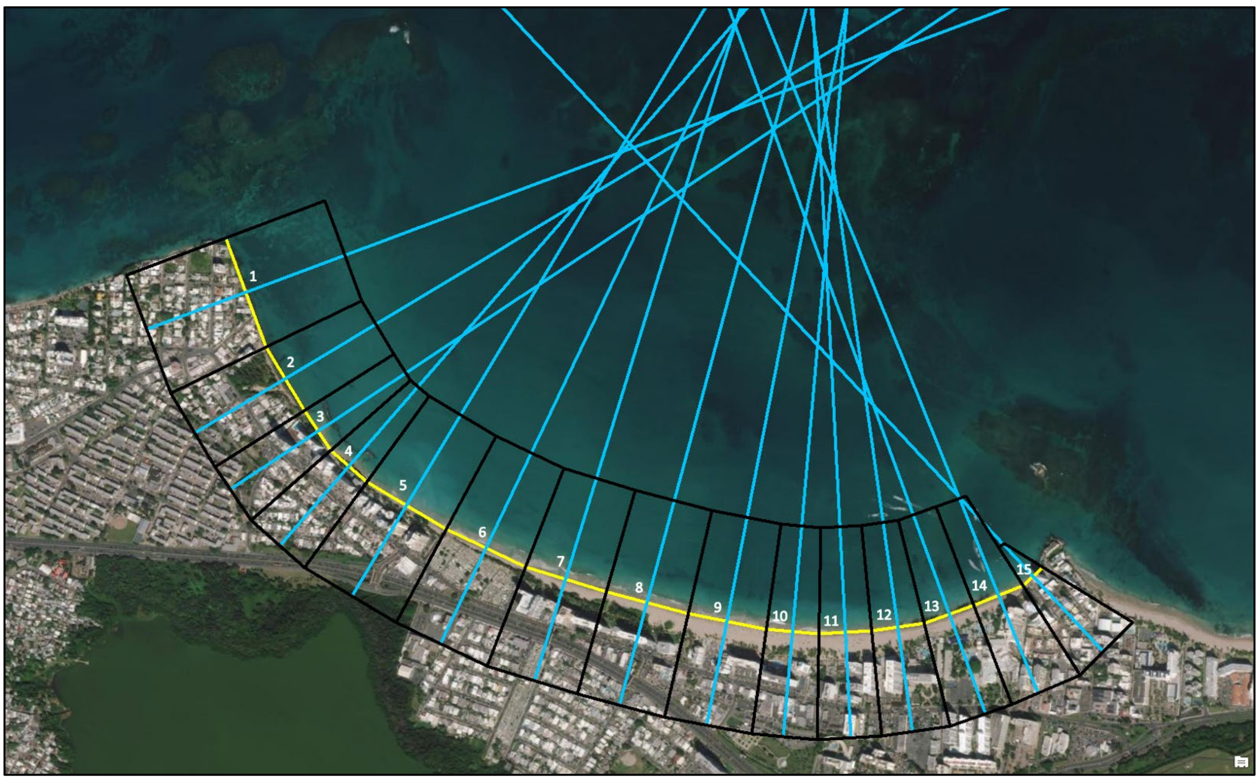


**Figure A-85. Beach-*fx* Isla Verde Model Area and Profile Locations**

**Table A-26. Idealized FWOP Profiles for the Beach-*fx* Rincón Model**

| Profile | Model Reach | Upland Elevation (ft PRV02) | Dune Elevation (ft PRV02) | Dune Width (ft) | Berm Elevation (ft PRV02) | Berm Width (ft) |
|---|---|---|---|---|---|---|
| RN05 | R11, R13-R14, R17, R22 | 7 | 7 | 20 | 3 | 0 |
| RN06 | R12, R15-R16, R18-R21 | 8 | 8 | 20 | 3 | 0 |


**Figure A-86. Beach-*fx* Rincón Model Area and Profile Locations**

#### 4.2.2.2 SBEACH Methodology

SBEACH 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. SBEACH is a 2D model that considers only cross-shore sediment transport. The model assumes that simulated profile changes are produced only by cross-shore processes. Longshore wave, current, and sediment transport processes are not included.

SBEACH is an empirically based numerical model, which was formulated using both field data and the results of large-scale physical model tests. Input data required by SBEACH describes the storm being simulated and the beach of interest. Basic requirements include time histories of wave height, wave period, water elevation, beach profile surveys, and median sediment grain size. SBEACH simulations are based on six basic assumptions:

- Waves and water levels are the major causes of sand transport and profile change.
- Cross-shore sand transport takes place primarily in the surf zone.
- The amount of material eroded must equal the amount deposited (conservation of mass).
- Relatively uniform sediment grain size is assumed throughout the profile.
- The shoreline is straight, and longshore effects are negligible.
- Linear wave theory is applicable everywhere along the profile without shallow-water wave approximations.

Once applied, SBEACH allows for variable cross shore grid spacing, wave refraction, randomization of input waves conditions, and water level setup due to wind. 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).

#### 4.2.2.3 SBEACH Calibration and Verification

Calibration and verification of SBEACH is typically achieved by developing input waves and water levels for known historical events and then tuning and verifying model parameters such that modeled post-storm profiles are in good agreement with measured post-storm survey data. For this study, insufficient measured data was available for calibration and verification. Therefore, SBEACH was applied using default settings except for grain size. A representative grain size was determined for and applied to each project segment. Median grain sizes for Condado, Ocean Park, Isla Verde, and Rincón were 0.26 millimeters (mm), 0.21 mm, 0.14 mm, and 0.31 mm, respectively.

#### 4.2.2.4 Long-Term Shoreline Changes

Historic shoreline changes (also known as “background erosion rates” or BERs) are typically long-term shoreline changes in an area of interest. BERs help define applied erosion rates (AER) in Beach-*fx*, which is the rate of change at the reach level used to calibrate non-storm induced erosion. AERs act as a balance between typical shoreline changes over time (BERs) and shoreline changes from model-applied storms. This balance is computed during Beach-*fx* calibration (Section 4.2.2.4.1) and depends on BERs by reach that are defined by the modeler. BERs for an area are generally best defined by continuously repeated (i.e., yearly, every 5 years, every decade, etc.) topographic and bathymetric surveys collected in the same location. However, long-term, repeated surveys were not available for the San Juan and Rincón study areas. Thus, the information and data detailed in Section 2.2.2 were used to quantitatively define the long-term erosion for Beach-*fx* modeling.

Data for San Juan included the Deltares (2019) white paper and associated data, where shoreline detection methods such as satellite imagery stitching and comparison were used to develop a comprehensive database of shoreline erosion and accretion rates from 1984-2019. Other information used to compile long-term erosion rates in San Juan include Google Earth (2022), USACE 2016 and 2018 LiDAR, and the CostaVisPR (2019) aerial photograph comparison tool. Long-term shoreline response (erosion or accretion) in San Juan is generally small (no change at headlands over the past 90 years and minimal shoreline erosion in much of the pocket beach centers). Table A-27 shows that for the three models built in San Juan, the least amount of measured long-term erosion occurred (on average) in Isla Verde and the largest amount (on average) in Ocean Park.

**Table A-27. Background Erosion Rates by Model Reach in San Juan, Puerto Rico**

| Model Reach | Erosion Rate (ft/yr); - Landward, + Seaward | | |
|---|---|---|---|
| | Condado (West to East) | Ocean Park (West to East) | Isla Verde (East to West) |
| 1 | -0.01 | -0.24 | 0.00 |
| 2 | -0.41 | -1.34 | 0.00 |
| 3 | -0.51 | -2.44 | 0.00 |
| 4 | -0.61 | -2.25 | -0.09 |
| 5 | -0.41 | -0.05 | -0.18 |
| 6 | -0.43 | -0.05 | 0.00 |
| 7 | -0.37 | -0.69 | 0.00 |
| 8 | -0.31 | -1.34 | 0.00 |
| 9 | -0.01 | -1.40 | -0.04 |
| 10 | - | -1.39 | -0.37 |
| 11 | - | -1.11 | -0.69 |
| 12 | - | -0.79 | -0.39 |
| 13 | - | -0.73 | -0.09 |
| 14 | - | -0.73 | -0.31 |
| 15 | - | -0.73 | -0.43 |
| 16 | - | -1.43 | - |
| 17 | - | -1.30 | - |
| 18 | - | -1.89 | - |
| 19 | - | -2.53 | - |
| 20 | - | -1.15 | - |
| 21 | - | -0.57 | - |
| 22 | - | 0.00 | - |

Thieler, et al. (2007) provided the best and most comprehensive long-term shoreline change information for Rincón. The data collected in that report showed BERs in the Rincón study area from 1936-2006 (Figure A-50) was roughly -1.3 ft/yr. However, other available data and periods were assessed to account for an uncertainty in those data of roughly 50 percent (+/-0.6 ft/yr) and to ensure more recent trends after 2006 were like older trends reported in that work. Thieler et al. (2007) also reported a shorter period from 1994 to 2006, and Google Earth (2022) provided more recent shoreline information from 1993 to 2019. The final BERs that were used in the Rincón Beach-*fx* modeling resulted from averaging these data. Figure A-87 displays these values by reach, where positive values represent accretion in feet per year (ft/yr) and negative values represent erosion in ft/yr. The area that is considered most erosive is at the south end of the study area in Corcega from R19 to R22, but the average shoreline erosion from R11 to R22 is -2.06 ft/yr.

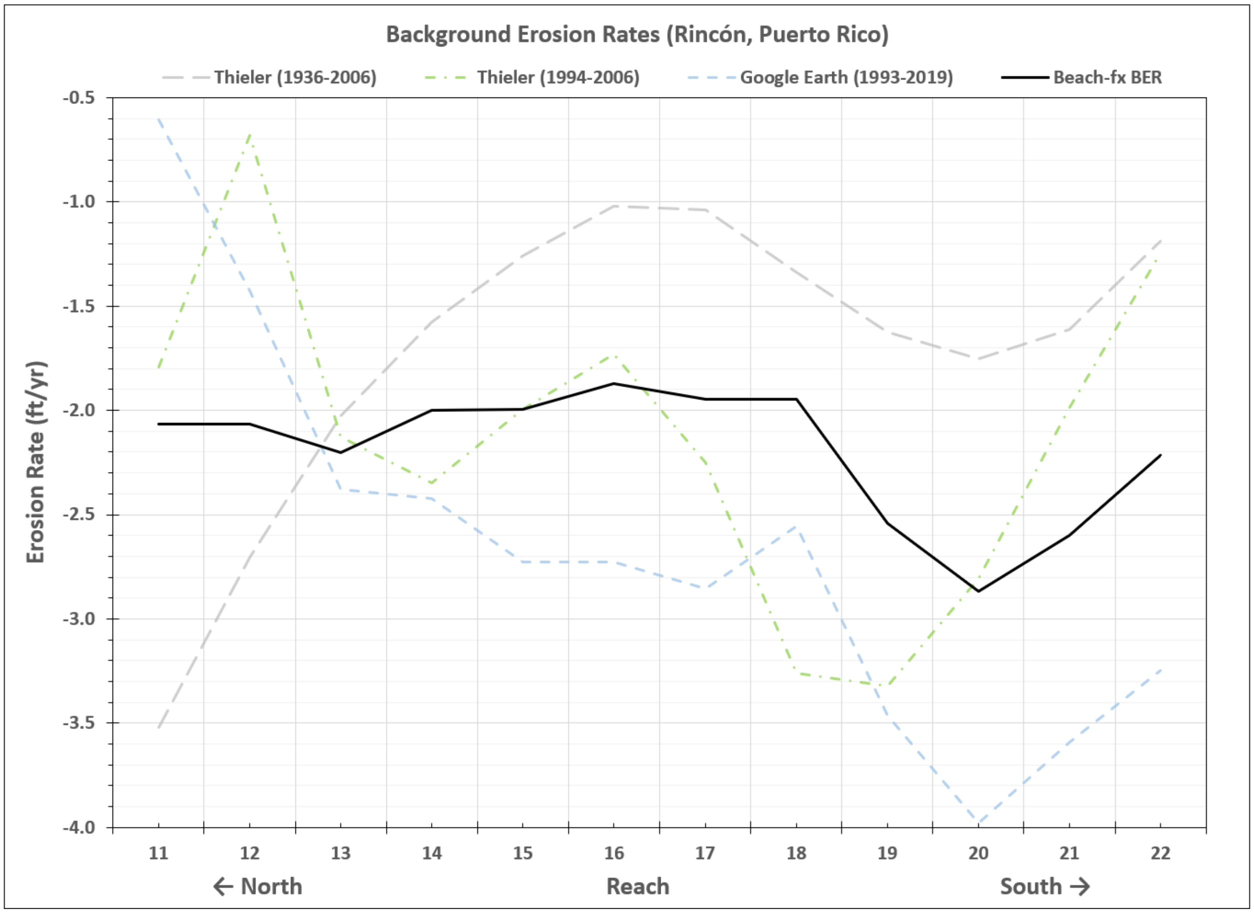


**Figure A-87. Long-Term Erosion in Rincón, Puerto Rico by Study Area Modeling Reach**

#### *4.2.2.4.1 Applied Erosion Rates*

The applied shoreline change rate (in ft/yr) 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.

During Beach-*fx* calibration, AER were adjusted for each model reach and the Beach-*fx* model was run repeatedly for 300 iterations over a 50-year period of analysis. 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. To obtain BERs for each model reach, erosion rates at each FDEP monument within that model reach were averaged. Table A-28 and

Table A-29 provide the historic BERs, storm-induced change rates (isolated by running the model with applied rates set to zero), and the final calibrated Beach-*fx* applied erosion rates for each project segment.

It is through the AER that SLC is incorporated into the Beach-*fx* shoreline change simulations. The calibrated applied erosion rates, based on historical shoreline change and the existing measured sea level rate of change, represents the baseline (low) SLC condition. Adding the change in shoreline recession for the intermediate and high SLC scenarios as predicted by Bruun's Rule to the calibrated applied erosion rates at each Model Reach, adjusts shoreline response for rising water levels. Earlier versions of the Beach-

*fx* model required the user to calculate adjustments external to the model and manually enter revised applied erosion rate values prior to model runs. However, the current version of Beach-*fx* performs the applied erosion rate adjustments internally, allowing all three SLC scenarios to be run within the same model setup.

**Table A-28. Calibrated AERs for San Juan's Beach-*fx* Models**

| Project Segment | Model Reach | Historical Background Change Rate (ft/yr) | Storm Induced Change Rate (ft/yr) | Calibrated Beach-*fx* Applied Erosion Rates (ft/yr) |
|---|---|---|---|---|
| Condado | R01 | 0.000 | -2.514 | 2.162 |
| | R02 | -0.410 | -2.561 | 1.824 |
| | R03 | -0.510 | -2.272 | 1.497 |
| | R04 | -0.610 | -1.798 | 0.749 |
| | R05 | -0.410 | -2.300 | 1.698 |
| | R06 | -0.430 | -2.300 | 1.692 |
| | R07 | -0.370 | -2.373 | 1.729 |
| | R08 | -0.310 | -2.373 | 1.808 |
| | R09 | 0.000 | -1.798 | 1.535 |
| Ocean Park | E01 | -0.240 | -1.419 | 1.207 |
| | E02 | -1.340 | -1.449 | 0.071 |
| | E03 | -2.440 | -1.449 | -1.020 |
| | E04 | -2.250 | -1.927 | -0.342 |
| | E05 | -0.050 | -2.118 | 2.015 |
| | E06 | -0.050 | -2.118 | 2.015 |
| | E07 | -0.690 | -0.83 | 0.168 |
| | E08 | -1.340 | -0.83 | -0.568 |
| | E09 | -1.400 | -0.263 | -1.137 |
| | E10 | -1.390 | -0.362 | -1.031 |
| | E11 | -1.110 | -0.366 | -0.760 |
| | E12 | -0.790 | -0.366 | -0.426 |
| | E13 | -0.730 | -0.366 | -0.379 |
| | E14 | -0.730 | -0.362 | -0.368 |
| | E15 | -0.730 | -0.362 | -0.368 |
| | E16 | -1.430 | -0.362 | -1.159 |
| | E17 | -1.300 | -0.362 | -0.966 |
| | E18 | -1.890 | -0.362 | -1.626 |
| | E19 | -2.530 | -0.362 | -2.259 |
| | E20 | -1.150 | -0.362 | -0.875 |
| | E21 | -0.570 | -0.362 | -0.235 |
| | E22 | 0.000 | -0.263 | 0.263 |

| Project Segment | Model Reach | Historical Background Change Rate (ft/yr) | Storm Induced Change Rate (ft/yr) | Calibrated Beach-*fx* Applied Erosion Rates (ft/yr) |
|---|---|---|---|---|
| Isla Verde | R01 | -0.434 | -2.464 | 2.354 |
| | R02 | -0.312 | -1.305 | 2.841 |
| | R03 | -0.089 | -1.305 | 4.025 |
| | R04 | -0.390 | -1.321 | 1.514 |
| | R05 | -0.690 | -1.321 | 0.496 |
| | R06 | -0.045 | -2.485 | 4.486 |
| | R07 | -0.045 | -2.485 | 4.486 |
| | R08 | 0.000 | -3.185 | 4.788 |
| | R09 | 0.000 | -1.321 | 4.411 |
| | R10 | 0.000 | -3.185 | 4.788 |
| | R11 | -0.178 | -3.185 | 4.407 |
| | R12 | -0.091 | -2.778 | 4.451 |
| | R13 | 0.000 | -2.778 | 4.622 |
| | R14 | 0.000 | -2.346 | 5.984 |
| | R15 | 0.000 | -7.945 | 9.012 |

**Table A-29. Calibrated AERs for Rincón's Beach-*fx* Models**

| Project Segment | Model Reach | Historical Background Change Rate (ft/yr) | Storm Induced Change Rate (ft/yr) | Calibrated Beach-*fx* Applied Erosion Rates (ft/yr) |
|---|---|---|---|---|
| Rincón | R11 | -2.063 | -10.227 | -2.261 |
| | R12 | -2.067 | -9.575 | -2.234 |
| | R13 | -2.203 | -10.227 | -2.299 |
| | R14 | -1.999 | -10.227 | -2.242 |
| | R15 | -1.993 | -9.575 | -2.209 |
| | R16 | -1.874 | -9.575 | -1.804 |
| | R17 | -1.947 | -10.227 | -2.227 |
| | R18 | -1.946 | -9.575 | -2.183 |
| | R19 | -2.542 | -9.575 | -2.753 |
| | R20 | -2.868 | -9.575 | -2.985 |
| | R21 | -2.601 | -9.575 | -2.767 |
| | R22 | -2.218 | -10.227 | -2.306 |

#### 4.2.2.5 Post-Storm Berm Recovery

Post-storm recovery of the eroded berm width after 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 interval. 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).

#### 4.2.2.6 Beach-*fx* Emergency Nourishment

Emergency nourishments are generally limited beach fill projects conducted by local governments in response to storm damage. Puerto Rico has not ever nourished the San Juan or Rincón coastlines. Therefore, emergency nourishment was not included in the Beach-*fx* analysis.

#### 4.2.2.7 Beach-*fx* 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 model 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.

#### *4.2.2.7.1 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 (traditional "advance fill"), or the berm trigger can be set to allow minimal or no erosion of the berm allowing the project interval and mobilization threshold volume to govern the renourishment cycle. For the Puerto Rico Coastal Study, the latter method was employed, and the berm trigger was set to 1.0 (0 percent loss). The dune width and dune height triggers were set to allow minimal erosion to the dune. The dune width and dune height triggers were set to 0.99 (1 percent loss of width) and 0.90 (10 percent loss of height), respectively.

#### *4.2.2.7.2 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 4 years will cause the model to evaluate nourishment distance triggers in year 4 of the period of analysis and if the triggers or volume threshold are not met, the model will not evaluate the triggers again until year 8.

The mobilization threshold (minimum nourishment volume required to initiate a nourishment cycle) is specified in cubic yards (cy). 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 and dune triggers 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. By setting the project interval to the minimum of 1 year, it 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.

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 cy), 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. Due to the random generation of storms within the model, these requirements will vary between renourishment events. In defining the project, the average renourishment volume is determined based on events occurring over multiple iterations of the project lifecycle.

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.

For this study, it was determined that the best approach to screening the alternatives was to vary the project interval while applying a low threshold volume.

#### *4.2.2.7.3 Planned Nourishment Templates*

Based on FWOP model results, the Condado and Isla Verde project segments were screened out for planned nourishment. Table A-30 and Table A-31 provide planned nourishment template dimensions for the initial array of FWP project alternatives developed for the Ocean Park and Rincón project segments.

**Table A-30. FWP Alternative Templates for Ocean Park**

| FWP Template | Dune Height (ft PRV02) | Dune Width (ft) | Berm Width (XX) (ft) |
|---|---|---|---|
| OP_DE_BXX | Existing | Existing | 10,20,30,40,50, 60,70,80,90,100 |
| OP_H8_W10_BXX | 8 | 10 | 10,20,30 |
| OP_H8_W20_BXX | 8 | 20 | 10,20,30 |
| OP_H10_W10_BXX | 10 | 10 | 10,20,30 |
| OP_H10_W20_BXX | 10 | 20 | 10,20,30 |
| OP_H12_W10_BXX | 12 | 10 | 10,20,30 |
| OP_H12_W20_BXX | 12 | 20 | 10,20,30 |

**Table A-31. FWP Alternative Templates for Rincón**

| FWP Template | Dune Height (ft PRV02) | Dune Width (ft) | Berm Width (XX) (ft) |
|---|---|---|---|
| RN_DE_BXX | Existing | Existing | 10,20,30,40,50, 60,70,80,90,100 |
| RN_H12_W10_BXX | 12 | 10 | 10,20,30 |
| RN_H12_W20_BXX | 12 | 20 | 10,20,30 |
| RN_H14_W10_BXX | 14 | 10 | 10,20,30 |
| RN_H14_W20_BXX | 14 | 20 | 10,20,30 |

#### *4.2.2.7.4 Project Induced Shoreline Change*

The project induced shoreline change rate accounts for the alongshore dispersion of placed beach nourishment material. Beach-*fx* requires the use of shoreline change rates to represent the planform diffusion of the beach fill alternatives after placement. Traditionally the 1D shoreline change model GENESIS (Hanson and Kraus, 1989) or GenCade (Frey et al., 2012), PC-based programs capable of simulating long term spatial changes in longshore transport, have 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.

To bring the analysis in line with the accelerated schedules required under SMART Planning guidelines, an alternative methodology was employed. Engineering Manual EM 1110-2-3301 Design of Beach Fills (USACE, 1995b) provides guidance on the selection of shoreline change models. Four acceptable alternatives are discussed:

- GENESIS – One-dimensional model (PC based)
- Dean and Yoo (1992) – One-line analytical model (spreadsheet/calculator based)
- Multi-contour 3D – Three-dimensional model with variable profile and longshore capabilities (PC based)
- Fully 3D Model – Three-dimensional model that calculate waves and currents in addition to sediment transport (PC based)

Of the alternatives, the one-line analytical model is the only one that accommodates SMART Planning schedule and budget constraints. This methodology produces valid, although idealized, estimates of planform diffusion for variable fill widths and lengths. It should be noted that the governing equation within the GENESIS and GenCade models is a one-line analytical solution.

#### *4.2.2.7.5 One Line Analytical Model*

While Dean and Yoo provides the basic governing formulations for assessing shoreline change rates, it does not specify a discrete analytical solution. These governing formulations, based on the conservation of sand combined with sediment transport, have existed for several decades. In that time, many analytical solutions have been developed to solve them. Because the analytical solution presented by Larson et al. (1987) is the closest in formulation to the GENESIS and GenCade models traditionally used in more complex USACE applications, it was selected as the one-line model for use with the Ponte Vedra Beach project.

The analytical solution for shoreline evolution derived by Larson et al. can be described by:

$$y(x,t) = \frac{1}{2} y_o \left[ erf\left(\frac{a-x}{2\sqrt{\varepsilon t}}\right) + erf\left(\frac{a+x}{2\sqrt{\varepsilon t}}\right)\right]$$

Where:

- $a$ = one half of the length of the fill
- $y_o$ = original cross-shore width of the fill
- $x$ = long-shore distance (where $x = 0$ is the center point of the fill)
- $t$ = time (where t = 0 is initial placement)
- $\varepsilon$ = diffusion coefficient.

The diffusion coefficient is defined as:

$$\varepsilon = \frac{2Q}{(h_* + B)}$$

Where:

- $h^*$ is depth of closure
- $B$ is the elevation of the berm
- $Q$ can be computed using the CERC equation, given as:

$$Q = \frac{K H_b^{\frac{5}{2}} \sqrt{\frac{g}{\lambda}} \sin(2\theta)}{16(s-1)(1-p)}$$

Where:

- $K$ = non-dimensional sediment transport proportionality factor
- $H_b$ = breaker height
- $g$ = acceleration due to gravity
- $\lambda$ = breaking wave height proportionality factor
- $\theta$ = angle of wave approach
- $s$ = specific gravity of sediment
- $p$ = porosity of sediment.

#### *4.2.2.7.6 Breaker Wave Height*

The breaker wave height is an estimate of the height of waves as they arrive and break on a given beach. This parameter is typically calculated analytically based on deep-water wave characteristics (USACE, 1984). However, in this case the measured background (historical) shoreline change rates are used to calibrate the analytical solution. The value of Hb becomes independent of the analytical results during the calibration process as the $KH_b$ factor becomes a tunable combined parameter for obtaining agreement between the measured data and analytical estimates.

#### *4.2.2.7.7 Wave Angle*

Wave angle like the breaker wave height is normally a value determined from measured data. This parameter also becomes independent of analytical results during the calibration process. Therefore, the wave angle was set to 45°, which results in maximum dispersion.

#### *4.2.2.7.8 $KH_b^{\frac{5}{2}}$ Parameter*

The sediment transport coefficient *K* can be highly variable. It is dependent on sediment characteristics, properties of the suspension medium, and local wave climate. Small changes in any of the environmental or sediment factors can have a significant impact on the value of *K*. Given the variability, the one-line model is calibrated by specifying *K* and $H_b$ as a combined factor, adjusted to maximize replication of measured shoreline change rates.

#### *4.2.2.7.9 Calibration*

To apply a one-line model, it is necessary to calibrate the model using the available data. For Ocean Park and Rincón, previously determined historical BERs were applied. Past applications of the one-line model have shown that as a fill equilibrates, the dispersion rate decreases until it approximates the BER when the project berm width reaches approximately 10 to 20 feet in width. Assuming the lower end of this range, $H_b$ and *K* values were varied to give the "best fit" to average BERs for the full extent of the project segments. The $KH_b$ factor

$$KH_b^{\frac{5}{2}}$$

for Ocean Park and Rincón calibrated to 0.55 and 8.3, respectively.

#### *4.2.2.7.10 FWP Planform Rates*

The significant difference between the values is attributable to the background erosional behavior of a pocket beach (Ocean Park) versus an open coastline (Rincón) and the difference in cross-shore profile dimensions. Despite this difference, resulting planform rates (Table A-32 to Table A-33) show reasonable and comparable dispersion for the given range of berm widths.

**Table A-32. Planform Rates - Ocean Park**

| Model Reach | Planform (Dispersion) Rates by Berm Width - Ocean Park | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10ft | 20ft | 30ft | 40ft | 50ft | 60ft | 70ft | 80ft | 90ft | 100ft |
| E10 | -1.71 | -3.41 | -5.12 | -6.82 | -8.53 | -10.23 | -11.94 | -13.65 | -15.35 | -17.06 |
| E11 | -1.34 | -2.67 | -4.01 | -5.34 | -6.68 | -8.02 | -9.35 | -10.69 | -12.03 | -13.36 |
| E12 | -1.04 | -2.08 | -3.11 | -4.15 | -5.19 | -6.23 | -7.27 | -8.31 | -9.34 | -10.38 |
| E13 | -0.83 | -1.67 | -2.50 | -3.34 | -4.17 | -5.01 | -5.84 | -6.68 | -7.51 | -8.35 |
| E14 | -0.73 | -1.47 | -2.20 | -2.93 | -3.67 | -4.40 | -5.13 | -5.87 | -6.60 | -7.33 |
| E15 | -0.73 | -1.47 | -2.20 | -2.93 | -3.67 | -4.40 | -5.13 | -5.87 | -6.60 | -7.33 |
| E16 | -0.83 | -1.67 | -2.50 | -3.34 | -4.17 | -5.01 | -5.84 | -6.68 | -7.51 | -8.35 |
| E17 | -1.04 | -2.08 | -3.11 | -4.15 | -5.19 | -6.23 | -7.27 | -8.31 | -9.34 | -10.38 |
| E18 | -1.34 | -2.67 | -4.01 | -5.34 | -6.68 | -8.02 | -9.35 | -10.69 | -12.03 | -13.36 |
| E19 | -1.71 | -3.41 | -5.12 | -6.82 | -8.53 | -10.23 | -11.94 | -13.65 | -15.35 | -17.06 |

**Table A-33. Planform Rates - Rincón**

| Model Reach | Planform (Dispersion) Rates by Berm Width - Rincon | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 10ft | 20ft | 30ft | 40ft | 50ft | 60ft | 70ft | 80ft | 90ft | 100ft |
| R11 | -2.26 | -4.51 | -6.77 | -9.02 | -11.28 | -13.53 | -15.79 | -18.04 | -20.30 | -22.55 |
| R12 | -2.17 | -4.34 | -6.50 | -8.67 | -10.84 | -13.01 | -15.17 | -17.34 | -19.51 | -21.68 |
| R13 | -2.07 | -4.15 | -6.22 | -8.30 | -10.37 | -12.45 | -14.52 | -16.60 | -18.67 | -20.75 |
| R14 | -2.01 | -4.01 | -6.02 | -8.02 | -10.03 | -12.04 | -14.04 | -16.05 | -18.05 | -20.06 |
| R15 | -1.96 | -3.92 | -5.88 | -7.84 | -9.80 | -11.76 | -13.72 | -15.68 | -17.64 | -19.60 |
| R16 | -1.95 | -3.89 | -5.84 | -7.79 | -9.73 | -11.68 | -13.63 | -15.57 | -17.52 | -19.47 |
| R17 | -1.95 | -3.89 | -5.84 | -7.79 | -9.73 | -11.68 | -13.63 | -15.58 | -17.52 | -19.47 |
| R18 | -1.97 | -3.94 | -5.91 | -7.89 | -9.86 | -11.83 | -13.80 | -15.77 | -17.74 | -19.71 |
| R19 | -2.01 | -4.02 | -6.04 | -8.05 | -10.06 | -12.07 | -14.08 | -16.10 | -18.11 | -20.12 |
| R20 | -2.08 | -4.16 | -6.24 | -8.32 | -10.40 | -12.48 | -14.56 | -16.64 | -18.72 | -20.80 |
| R21 | -2.14 | -4.29 | -6.43 | -8.58 | -10.72 | -12.87 | -15.01 | -17.15 | -19.30 | -21.44 |
| R22 | -2.22 | -4.44 | -6.65 | -8.87 | -11.09 | -13.31 | -15.52 | -17.74 | -19.96 | -22.18 |

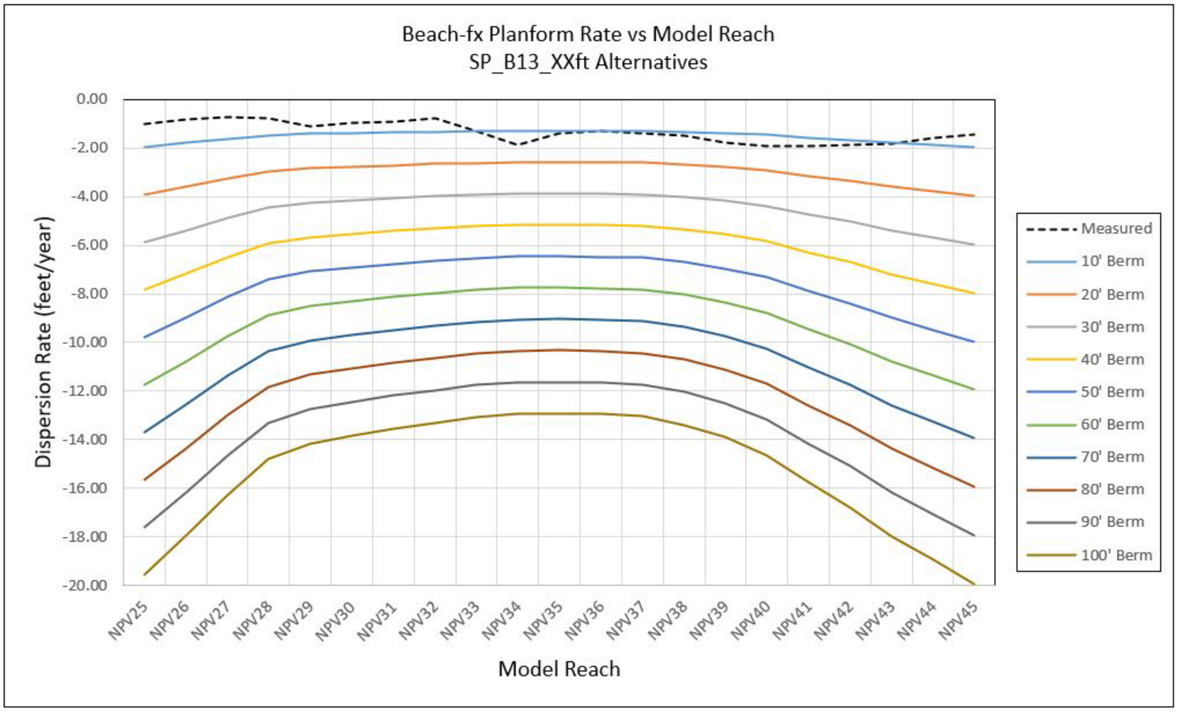


**Figure A-88. Beach-*fx* Platform Rate vs Model Reach**

## 4.3 Generation II Coastal Risk Model Input

G2CRM is a computer model that implements an object-oriented Probabilistic Life-Cycle Analysis model using an event-driven Monte Carlo Simulation. This allows for incorporation of time-dependent and stochastic event-dependent behaviors such as SLC, tides, and structure raising and/or removal. The model is based on damage driving forces (storms) that affect a coastal region (study area). The study area can be comprised of individual sub-areas (G2CRM model areas) that may interact hydraulically and may be protected by coastal defense measures that serve to shield the areas and the assets they contain from storm damage (USACE, 2018b). To determine the damages for a specific event and time, G2CRM compares the total water level (sum of the storm surge, SLC, tide, and potential wave inputs) to asset FFEs within FWOP or PSE elevations and then FFEs within FWP conditions. G2CRM consists of multiple engineering inputs to accurately represent the study area which are described in the sections below. USACE, SAJ used the DEMs described within Section 1.3 to develop necessary inputs into G2CRM and influence the design of measures within the study area. The base year for the present Puerto Rico Coastal Study is 2029, and the model start year within G2CRM is 2022. The start year in G2CRM differs from Beach-*fx* in order to capture risk from storms and the associated changes in dynamic inventories between current conditions and the base year. See the Economics Appendix for more information regarding the development of the G2CRM economic inputs and start and base year assumptions. For additional details on the G2CRM model reference the Model Documentation for Certification (USACE, 2017b) and the G2CRM User's Manual (USACE, 2018b).

### *4.3.1 Protective System Elements*

A PSE is the infrastructure that defines the coastal boundary; be it a coastal defense system that protects the G2CRM model areas, defined in Section 4.1 and shown in Figure A-68, from coastal flooding (levees, pumps, closure structures, etc.) or a locally developed coastal boundary comprised of bulkheads and/or hardened shoreline (USACE, 2018b). The G2CRM PSE consists of various inputs to best represent the coastal boundary fronting the G2CRM model area and determine the inundation within the G2CRM model area. These inputs include the PSE top elevation, PSE length, and weir coefficient.

#### 4.3.1.1 San Juan

Within FWOP model setup, USACE, SAJ designated the PSEs within Condado and Isla Verde to encompass the entire extent of the G2CRM model areas adjacent to the flood source because of the consistently high elevations along the coast in both. The minimum DEM elevation along the PSE transects represented the input PSE top elevations for Condado and Isla Verde, this provided the best representation of existing conditions. Selecting the minimum elevation allows G2CRM to compare asset FFEs and interior water surface elevations to determine damages.

Ocean Park required a different methodology to determine the FWOP PSE length and PSE top elevation due to multiple flood paths into the G2CRM model area. For initial G2CRM input, the Ocean Park PSE length was the combined length of both flood paths, and the Ocean Park PSE top elevation was the minimum DEM elevation along the PSE transects. Water level output from HEC-RAS determined the refined Ocean Park PSE length and PSE top elevation to best represent the inundation within the G2CRM model area. HEC-RAS calculated the water levels within the G2CRM model area using the maximum output hydrograph from G2CRM with and without intermediate SLC. USACE selected the FWOP Ocean Park PSE top elevation and PSE length that provided the closest comparison to the HEC-RAS water levels inside the G2CRM model area. Table A-34 displays the FWOP PSE lengths and PSE top elevations for the G2CRM model areas. All G2CRM model areas used a weir coefficient of 1.6 to represent FWOP (natural ground conditions) and FWP (alternative conditions). The HEC-RAS 2D Modeling User's Manual (USACE, 2022f) justifies this assumption since our FWOP and FWP conditions are both 3 feet or higher above the natural ground.

To account for inundation damages in Ocean Park from the back-bay during high SLC model runs, USACE determined the PSE top elevation and PSE length by comparing water level outputs from HEC-RAS and the G2CRM stage outputs. HEC-RAS calculated the water levels within the G2CRM model area using the hydrographs from multiple G2CRM events driven from the back-bay (San Jose Lagoon). Table A-34 shows the PSE top elevation and PSE length for Ocean Park back-bay.

**Table A-34. FWOP PSE Inputs**

| Model Area Names | FWOP | |
|---|---|---|
| | PSE Top Elevations (ft PRVD02) | PSE Length (ft) |
| Condado | 8.0 | 3,253 |
| Ocean Park | 4.5 | 300 |
| Ocean Park Back-Bay | 4.5 | 830 |
| Isla Verde | 6.2 | 8,614 |
| Rincón | 7.0 | 7,522 |

Ocean Park was the only G2CRM model area to require FWP G2CRM modeling since it was the only G2CRM model area to receive substantial inundation damages within the FWOP model runs, therefore the Ocean Park PSE top elevation and PSE length required changes to represent each alternative and correspond to the correct design elevations. The analysis used the same methodology within FWOP to determine the FWP PSE lengths for the design alternatives, which consisted of 6 feet PRVD02, 7 feet PRVD02, and 8 feet PRVD02 floodwalls. Comparing the water level outputs from HEC-RAS and the G2CRM stage outputs USACE selected PSE lengths that provided the best representation of inundation within the G2CRM model area for each of the three design elevations. HEC-RAS calculated the water levels within the G2CRM model area using the hydrographs from three G2CRM events driven from the coast. Table A-35 displays the FWP PSE top elevation and PSE lengths within Ocean Park.

**Table A-35. FWP PSE Inputs**

| Model Area Name | FWP | |
|---|---|---|
| | PSE Top Elevations (ft PRVD02) | PSE Length (ft) |
| Ocean Park | 6.0 | 750 |
| | 7.0 | 1,625 |
| | 8.0 | 5,900 |

#### 4.3.1.2 Rincón

Like Condado and Isla Verde, the PSE within Rincón encompassed the entire extent of the G2CRM model area adjacent to the flood source because of the consistently high elevations along the coast. The minimum DEM elevation along the PSE represented the input PSE top elevation for the FWOP condition. The study did not require FWP model runs within G2CRM. The FWOP PSE top elevation and PSE length for Rincón are 7.0 feet PRVD02 and 7,522 feet, respectively.

### *4.3.2 Meteorological Forcing*

Meteorological forces are represented by storm hydrographs (surge and waves) at project locations and are generated externally from high-fidelity storm surge and nearshore wave models such as the ADCIRC and STeady-State Spectral WAVE (STWAVE) models (USACE, 2018b). Additionally, the number of storms per year and relative storm probability are incorporated into G2CRM, further described below.

#### 4.3.2.1 Storm Hydrographs San Juan

The storm database for San Juan consisted of 23 storms (16 tropical storms and 7 nor'easter storms). USACE selected tropical storms from CHS save point 14863 and the nor'easter storms from NDBC gauge 41053. The Beach-*fx* and G2CRM models employed the same 23 storms for consistency. For additional detail on the storm selection process within San Juan see Section 4.2.1. The storm suite representing potential flooding from the San Juan back-bay (San Jose Lagoon), for the Ocean Park back-bay G2CRM model area and high SLC model runs, included 15 tropical storms from CHS save point 2175. The Ocean Park back-bay storm suite did not include Storm 3065T because it contained an AEP water level event above 0.033 percent; based on CHS save point 2175. Additionally, the back-bay storm suite did not include nor'easter events because no water level or wave data within the San Jose Lagoon was available. Table A-36 displays the selected storms described above for both San Juan and Ocean Park back-bay. Figure A-88 and Figure A-89 display the hydrographs for both San Juan and Ocean Park back-bay, respectively.

**Table A-36. G2CRM San Juan and Ocean Park Back-Bay Storm Suite**

| Storm | Storm Type* | San Juan (CHS Save Point 14863) | | Ocean Park Back-Bay (CHS Save Point 2175) | |
|---|---|---|---|---|---|
| | | SWE (ft PRVD02) | Relative Probability | SWE (ft PRVD02) | Relative Probability |
| 3004T | TS | 2.1 | 0.011340 | 0.5 | 0.011370 |
| 3023T | TS | 1.7 | 0.027399 | 0.3 | 0.027473 |
| 3031T | TS | 2.0 | 0.012002 | 0.3 | 0.012034 |
| 3039T | TS | 1.7 | 0.070941 | 0.2 | 0.071131 |
| 3046T | TS | 1.6 | 0.028041 | 0.2 | 0.028116 |
| 3061T | TS | 2.4 | 0.001041 | 0.3 | 0.001043 |
| 3065T | TS | 4.5 | 0.001232 | - | - |
| 3067T | TS | 4.7 | 0.015084 | 0.7 | 0.015125 |
| 3072T | TS | 3.7 | 0.110957 | 2.4 | 0.111254 |
| 3074T | TS | 3.8 | 0.022954 | 0.8 | 0.023016 |
| 3129T | TS | 1.7 | 0.024763 | 0.2 | 0.024829 |
| 3164T | TS | 1.5 | 0.111035 | 2.1 | 0.111332 |
| 3191T | TS | 1.8 | 0.002612 | 0.2 | 0.002619 |
| 3192T | TS | 1.6 | 0.000707 | 0.1 | 0.000709 |
| 3238T | TS | 3.7 | 0.002275 | 1.1 | 0.002282 |
| 3299T | TS | 1.2 | 0.019221 | 0.3 | 0.019272 |
| 20150405ET1 | ET | 0.5 | 0.123288 | - | - |
| 20161218ET2 | ET | 0.4 | 0.369863 | - | - |
| 20170111ET3 | ET | 0.6 | 0.109589 | - | - |
| 20180305ET4 | ET | 0.8 | 0.013699 | - | - |
| 20190309ET5 | ET | 0.4 | 0.123288 | - | - |
| 20191101ET6 | ET | 0.7 | 0.123288 | - | - |
| 20201022ET7 | ET | 0.4 | 0.260274 | - | - |

*Storm types are designated either as tropical storm (TS) or extra-tropical/nor’easter storm (ET)

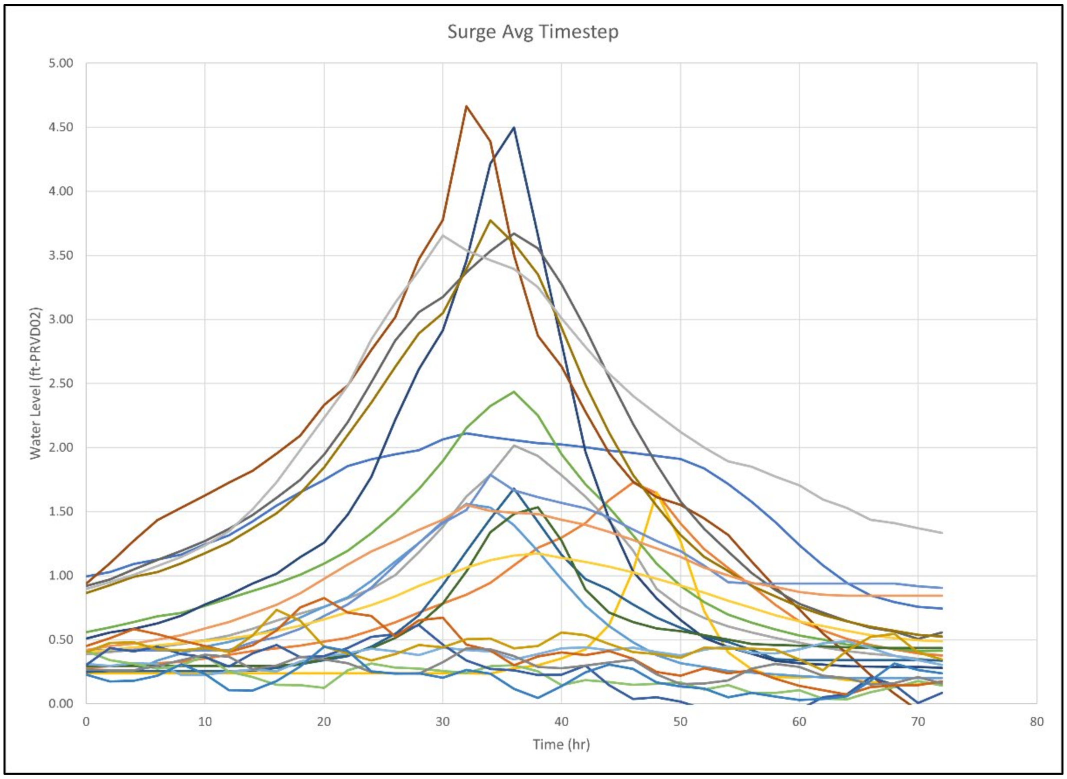


**Figure A-89. Storm Hydrographs for San Juan**

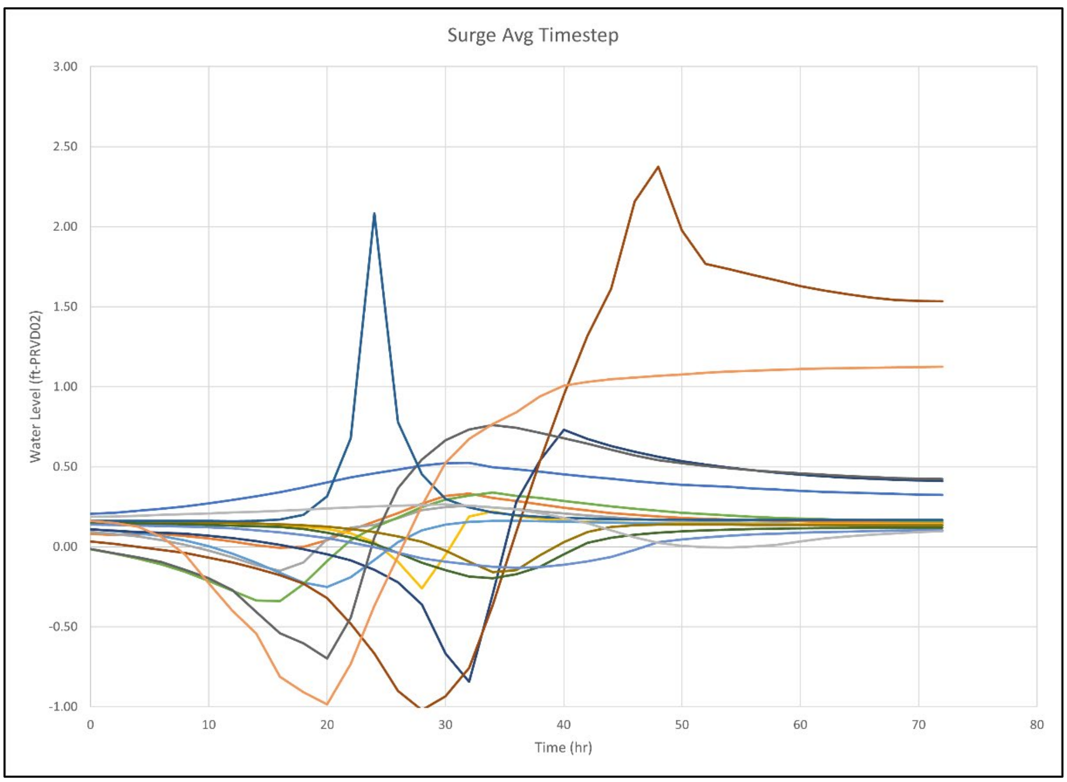


**Figure A-90. Storm Hydrographs for Ocean Park Back-Bay**

#### 4.3.2.2 Storm Hydrographs Rincón

The Rincón storm suite consists of 29 total storms, of which 22 are tropical storms and 7 are nor'easter storms. The storm selection process used CHS save point 488 to select tropical storms and a combination of OWI and NDBC (buoy 41115) data to select nor'easter storms. The Beach-*fx* and G2CRM models employed the same 29 storms for consistency. For additional details on the storm selection process within Rincón see Section 4.2.1. Table A-37 and Figure A-91 display the selected storms and hydrographs.

**Table A-37. G2CRM Rincón Storm Suite**

| Storm | Storm Type | Rincón (CHS Save Point 488) | |
|---|---|---|---|
| | | SWE (ft PRVD02) | Relative Probability |
| 3004T | TS | 2.0 | 0.001629 |
| 3009T | TS | 2.4 | 0.000021 |
| 3015T | TS | 0.9 | 0.040706 |
| 3051T | TS | 2.5 | 0.013336 |
| 3062T | TS | 0.7 | 0.060918 |
| 3074T | TS | 1.5 | 0.004576 |
| 3097T | TS | 0.5 | 0.004393 |
| 3098T | TS | 0.7 | 0.061291 |
| 3111T | TS | 0.9 | 0.043681 |
| 3139T | TS | 0.8 | 0.018511 |
| 3144T | TS | 0.8 | 0.035485 |
| 3150T | TS | 2.0 | 0.012157 |
| 3153T | TS | 1.4 | 0.037227 |
| 3156T | TS | 1.7 | 0.009143 |
| 3168T | TS | 1.2 | 0.011458 |
| 3198T | TS | 0.8 | 0.011611 |
| 3201T | TS | 0.3 | 0.017152 |
| 3205T | TS | 3.9 | 0.002891 |
| 3260T | TS | 3.3 | 0.002594 |
| 3267T | TS | 2.4 | 0.008960 |
| 3276T | TS | 1.8 | 0.000116 |
| 3278T | TS | 0.7 | 0.038602 |
| 20160121ET1 | ET | 0.5 | 0.152778 |
| 20160419ET2 | ET | 0.5 | 0.458333 |
| 20170102ET3 | ET | 0.5 | 0.277778 |
| 20170110ET4 | ET | 0.4 | 0.013889 |
| 20180304ET5 | ET | 1.7 | 0.013889 |
| 20200119ET6 | ET | 0.7 | 0.013889 |
| 20210130ET7 | ET | 0.4 | 0.069444 |

*Storm types are designated either as tropical storm (TS) or extra-tropical/nor’easter storm (ET)

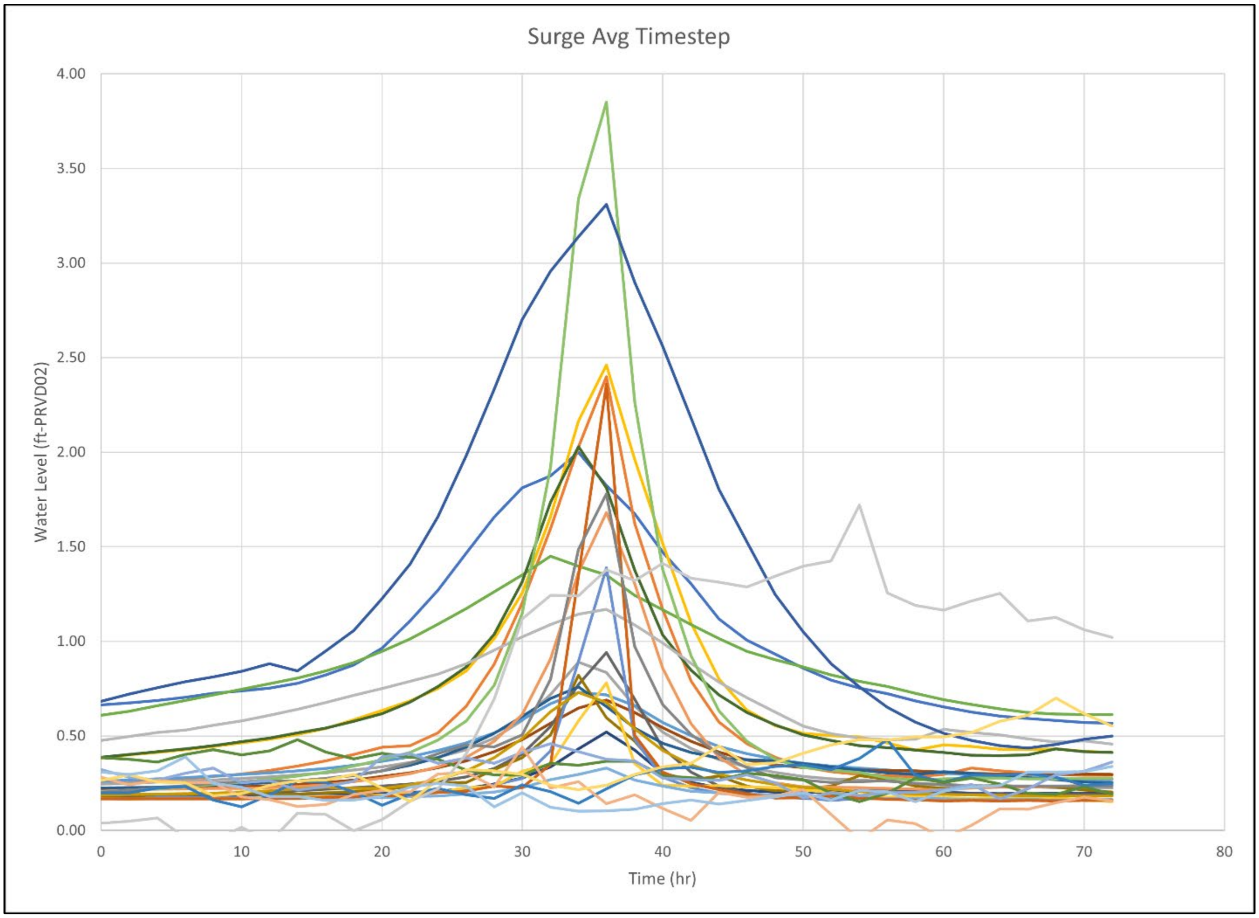


**Figure A-91. Storm Hydrographs for Rincón**

4.3.2.3 Wave Contribution

G2CRM contains multiple methodologies to account for wave contributions to the total water level. The modeler can choose between auto-generated depth limited wave heights based on input ground elevations or waves directly input into the model using wave data for each storm. When inputting wave data directly into the model, the program either uses the wave inputs as is or depth-limits the input waves. The wave data within CHS save point 14863 (San Juan) and CHS save point 488 (Rincón) are located offshore (at depths of approximately 30 feet) and therefore contain waves that are not yet depth-limited and would likely overestimate the wave contribution to the total water level within each G2CRM model area. Therefore, USACE used G2CRM's depth limited wave height option based on input G2CRM model area ground elevations. To ensure G2CRM employs this methodology, inputs need to be specified within the H5StormMetadata input file (IsStwaveFormat = 1 and UseWaveDataAsIs = 0).

To maintain consistency between G2CRM and Beach-*fx*, the selected ground elevations are based on the minimum berm or dune elevation within the SBEACH idealized profiles. Ocean Park and Isla Verde both contain dunes seaward of the assets, therefore G2CRM included ground elevations based on the lowest dune elevations within the SBEACH idealized profiles. Existing dunes are not present at Condado and Rincón, therefore USACE analyzed DEM elevations along profiles and the SBEACH idealized profile berm elevations to determine ground elevations. Elevations along these profiles generally matched the berm elevations within the SBEACH idealized profiles for Condado and Rincón. Additionally, G2CRM used a ground elevation for the Ocean Park back-bay G2CRM model area (this is the same G2CRM model area as Ocean Park) based on DEM elevations along a profile located at the back-bay entry points of the G2CRM model area. Table A-38 displays the ground elevation inputs, and Figure A-68 and Figure A-70 show the G2CRM model areas.

**Table A-38. G2CRM Ground Elevations**

| Model Area Names | Model Area Ground Elevations (ft PRVD02) |
|---|---|
| Condado | 3.0 |
| Ocean Park | 4.0 |
| Ocean Park Back-Bay | 4.0 |
| Isla Verde | 6.0 |
| Rincón | 4.0 |

#### 4.3.2.4 Relative Storm Probability

The relative storm probability within G2CRM differs from Beach-*fx*, for tropical storms, due to differences within the model applications. Beach-*fx* uses a relative probability based on a combination of both storm events and tides, while G2CRM only requires the relative probability for the input storm events. The storm selection process utilizes both the storm season inputs (described in Section 4.2.1.4) and relative storm probability inputs. To determine the storm event generation G2CRM first selects the tropical and nor'easter events that occur through each season within the year. The program uses the Poisson distribution to randomly select the number of storms that occur within each season based on the predetermined average number of storms in a season input, shown within Table A-22. After G2CRM selects the number of storms occurring in each season, the model then chooses which storms will occur in each season by randomly selecting storms out of the available storm suite using bootstrap sampling with replacement (higher probability storms are chosen more often). USACE, SAJ determined the relative storm probability for the tropical storms based on the CHS relative probability mass calculated by the U.S. Army Engineer Research and Development Center (ERDC) from the CHS save points. The analysis required the recalculation of the probability mass for the chosen tropical storms to determine the final relative probability. G2CRM and Beach-*fx* used the same relative storm probabilities for nor'easters and this process is further discussed in Section 4.2.1.3. The relative probability for each storm is shown within Table A-36 and Table A-37.

### *4.3.3 Astronomical Tides*

USACE, SAJ selected the NOAA tide station 9755371 (San Juan Bay, PR) for tidal input within the San Juan G2CRM model areas (Condado, Ocean Park, and Isla Verde) and the NOAA tide station 9759394 (Mayaguez, PR) for tidal input within Rincón. Additional details on the astronomical tides within San Juan and Rincón can be found in Section 2.1.1. Within the San Juan back-bay model runs a tidal station was not selected due to the limited tidal influence within the San Jose Lagoon; data collected by GLM Engineering COOP (2020) supports this assumption.

### *4.3.4 Sea-Level Change Rate and Curve*

Within the San Juan G2CRM model areas, the Puerto Rico Coastal Study implemented a relative sea level trend of 2.09 mm/yr (0.00686 ft/yr) based on the MSL trend at San Juan Bay, PR gauge 9755371. Within

Rincón a SLC rate of 1.90 mm/yr (0.00623 ft/yr) was input based on the MSL trend at Magueyes Island, PR gauge 9759110. G2CRM requires the selection either the low, intermediate, or high USACE SLC curves and internally applies the appropriate SLC equation dependent upon the scenario selection. The study ran the low, intermediate, and high SLC curves. For additional details on SLC, refer to Section 2.2.2.

#### *4.3.5 Stage-Volume Relationship and Input*

G2CRM has an optional data import tool for the stage-volume relationship, which is used to represent internal ponding within the G2CRM model area. If a stage-volume is not employed, G2CRM will instantaneously transmit the stage, above the input PSE top elevation, into the G2CRM model area. To accurately represent the coastal flooding into G2CRM model areas, G2CRM uses the weir equation to calculate a time-dependent volume transmitted into the G2CRM model area until the storage capacity within the G2CRM model area is filled; after which G2CRM transitions back to transmitting the stage unmediated into the G2CRM model area. Stage-volume curves are based on the DEM and determine the volume within each G2CRM model area in relation to various stage elevations.

### 4.4 Economic Input Overview

The Beach-*fx* and G2CRM models analyze the economics of CSRM studies based on the probabilistic nature of storm associated damages to structures in the study 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 protection elements. Within Beach-*fx*, damages are attributed to three mechanisms: erosion (through structural failure or undermining a foundation), flooding (through structure inundation levels), and waves (through the force of impact to armor or a structure). While damages within G2CRM are solely based on flooding.

Although wind may also cause shoreline changes, CSRM projects are not designed to mitigate for impacts due to wind. Therefore, the Beach-*fx* and G2CRM models do not include this forcing. Damages are calculated for each damage element following each storm that occurs during the model run. Within Beach-*fx*, erosion, water level, and maximum wave height profiles are determined for each individual storm from the lookup values in the previously stored storm-response database. These values are then used to calculate the damage driving parameters (erosion, inundation level, and wave height) for each damage element. Within G2CRM, damage functions are used to determine the damages to assets from inundation.

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 the structure contents. Damages 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* and G2CRM can be found in Appendix D: Economic Analysis.

### 4.5 Potential Management Measures for Puerto Rico

A wide range of CSRM measures were defined and assessed for general effectiveness in these areas. Both hard and soft measures were considered, and nature-based and non-structural measures were analyzed. A final array of CSRM alternatives consisted of nourishment, groins, revetment, seawalls, and non-structural measures.

### 4.5.1 Beach Nourishment

Beach nourishment is defined as the placement of sediment in the nearshore system or on the beach to extend the shoreline seaward. The advanced shoreline is intended to protect upland areas from erosion, wave attack, and flooding. Beach nourishment projects generally consist of a berm and dune feature designed to specific elevations and widths. Beach-quality sediment is placed through either dredging from borrow areas and/or truck haul from upland sand mines. Typically, initial beach nourishment projects are supplemented with periodic nourishments every few years to mitigate the background erosion by waves and currents. Figure A-92 shows an example of a beach nourishment project. For additional information and guidance on beach nourishment reference EM 1110-2-3301 (USACE, 1995b) and EM 1110-2-1100 (USACE, 2008b).

**Figure A-92. Example of Beach Nourishment in Sarasota County, FL**

### 4.5.2 Revetment

As described within EM 1110-2-1614 (USACE, 1995a), a revetment consists of erosion resistant material, generally stone or concrete, that is built to protect shoreline features against erosion. Revetments generally consist of three layers: armor layer, filter layer, and toe layer, however, large-scale revetments placed on ocean-front shorelines or areas with large coastal forces may include additional layers. The armor layer absorbs and dissipates wave energy, the filter layer is a porous layer that reduces erosion of the underlying sediment, and the toe layer protects the seaward portion of the revetment.

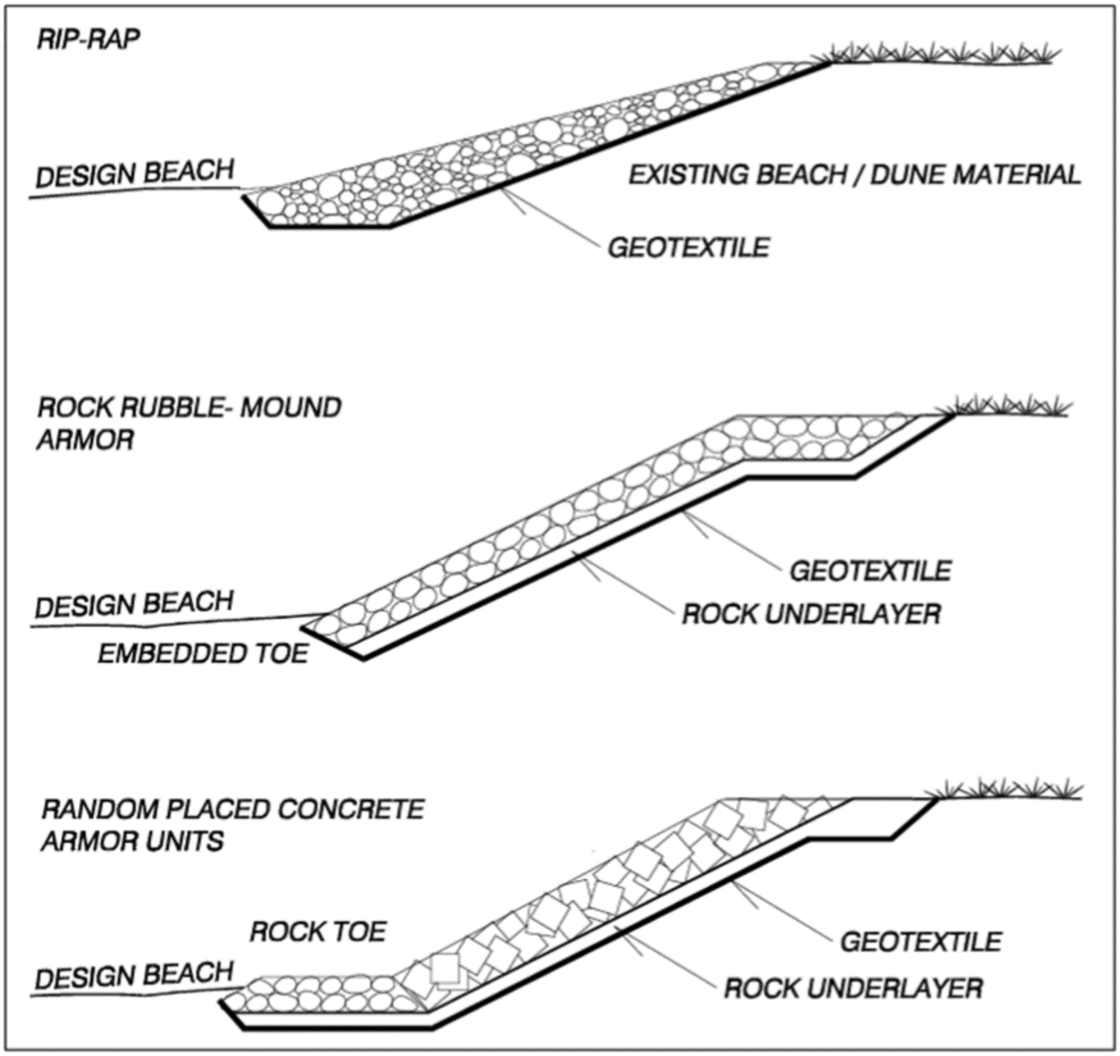


**Figure A-93. Example of Revetment (USACE, 2008b)**

### *4.5.3 Groins*

Groins are shore perpendicular structures, generally consisting of sheet pile and/or stone, that maintain sediment on the updrift side by impeding longshore sediment transport. These shore-perpendicular structures can cause downdrift erosion as the natural sediment transport is disrupted by these structures. Groins consisting solely of stone allow for some sediment transport which can reduce downdrift erosion, while sheet pile groins are impermeable and tend to increase downdrift erosion. These hard structures are generally used in combination with beach nourishment to allow the continuation of alongshore sediment transport and reduce erosion to landward structures. Due to the FWOP erosion damages within the Rincón study area groins were considered in combination with a beach nourishment measure. Figure A-94 displays an example of a groin in Sarasota County, FL. For additional information and guidance on groins reference EM 1110-2-1617 (USACE, 1992b) and EM 1110-2-1100 (USACE, 2008b).

**Figure A-94. Example of Groin in Sarasota County, FL**

*4.5.4 Floodwalls*

Floodwalls are vertical structures designed to reduce the risk of flooding and erosion to adjacent land and/or structures; they can also be designed to reduce the impacts of waves. Some examples of floodwalls consist of shallow foundation walls, deep foundation walls, cantilever pile walls, and pile walls with tieback/anchors. The most common structural materials found in floodwalls are timber, concrete, steel sheet piles, and structural anchors. The type and size of floodwalls is generally dependent on the difference between the structure floor elevation and the design flood event. Shallow and deep foundation walls are typically characterized as T-Walls, L-Walls, and I-Walls and generally consist of concrete. ETL 1110-2-575 (USACE, 2011) and ECB 2017-03 (USACE, 2017c) advises for the use of I-walls where the height of wall is to be 6 feet or less. L-Walls, sometimes referred to as kicker pile walls, can withstand an 8-foot flood event. T-Walls have no height limit, but typically are constructed when the height of the wall is greater than 4 feet. Cantilever pile walls and tieback walls are also referred to as seawalls and generally consist of steel sheet piles, a concrete cap, and tiebacks and anchors. For additional information and guidance on floodwalls reference EM 1110-2-1614 (USACE, 1995a) and EM 1110-2-2502 (USACE, 2022c). Figure A-95 and Figure A-96 display some examples of these structures.

**Figure A-95. Example I-Wall in City of Norfolk, VA**

**Figure A-96. Example T-Wall in Richmond, VA**

### *4.5.5 Non-Structural Considerations*

Non-structural measures are permanent or contingent measures applied to a structure and/or its contents that prevent or provide resistance to damage from flooding, erosion, and/or wave attack. Non-structural measures focus on reducing the consequences of flooding rather than reducing the probability of flooding.

These measures can consist of relocation, structure acquisition, dry proof flooding, wet floodproofing, emergency action planning, etc. Figure A-97 displays an example of a non-structural measure, relocation. The Puerto Rico Coastal Study considered structure acquisition within both the Rincón and San Juan study areas. Structure acquisition includes the purchasing of flood damageable structures and then relocation of inhabitants to locations away from storm-induced hazards. The acquired properties would be reestablished as natural coastline (beach) that would support environmental enhancement, public recreation, future economic growth/stability, and increase shoreline stability.

In addition to structure acquisition, it should also be accompanied by the local government establishing and enforcing a coastal regulatory program to regulate current and future coastal development. This could be modeled after the Coastal Construction Control Line (CCCL) Program administered by the FDEP in Florida, which ensures the reasonable use of private property by regulating structures and activities that can cause beach erosion, destabilize dunes, damage upland properties, or interfere with public access. The FDEP establishes the CCCL based on the landward limit of damaging effects of a one percent AEP storm event; everything seaward of the CCCL is subject to the FDEP regulations. The Puerto Rico Coastal Management Program developed the maritime terrestrial zone which establishes conditions as to how coastal-dependent uses may be developed. Although additional regulations are recommended to limit construction within the natural “beach” zone and restrict unauthorized construction activities too close to the shoreline.

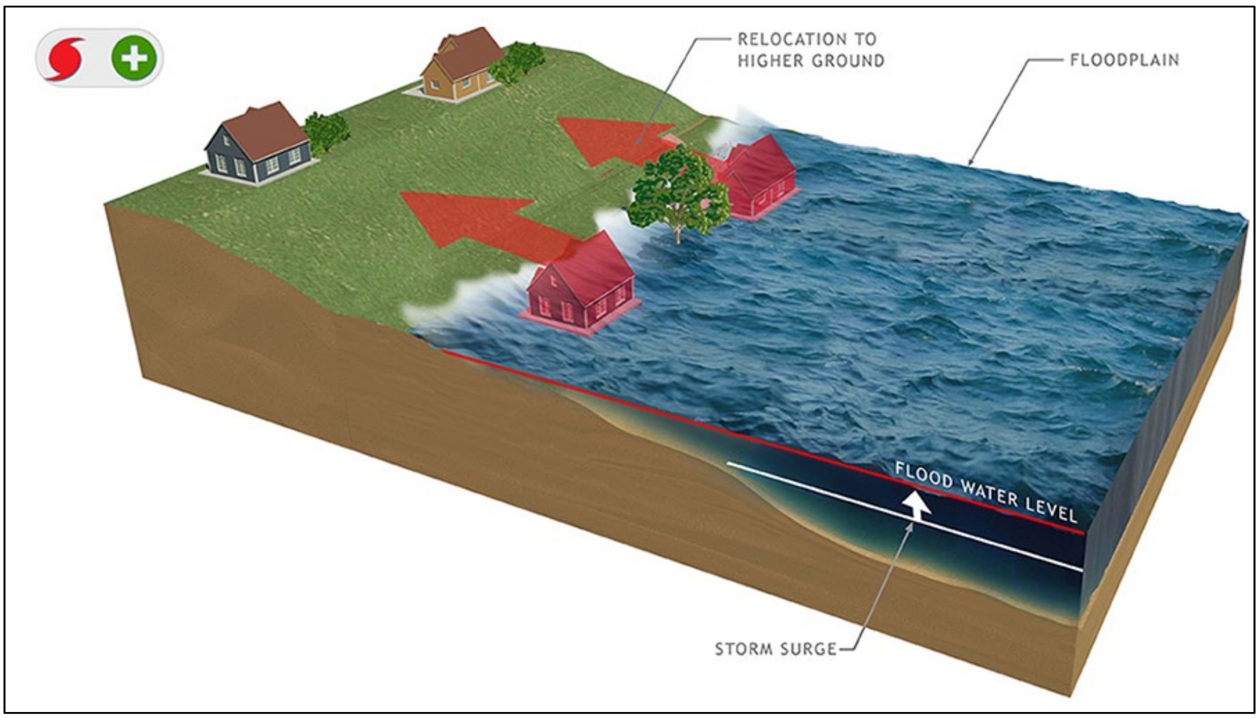


**Figure A-97. Non-Structural CSRM Measure Example (USACE, 2015)**

### *4.5.6 Breakwaters*

A management measure that USACE considered within initial plan formulation was a breakwater or a field of breakwaters for both study areas. The primary function of coastal breakwaters is to break and attenuate incoming wave energy before that energy hits the leeward coastline. Thus, these structures tend to reduce shoreline erosion by minimizing sand movement between the breakwater and the coastline when waves are the dominant driver of littoral sand transport. Breakwaters do not function as surge or relative SLC inundation protection, so they would not function optimally as standalone features in the San Juan study area since the offshore fringing reef already inherently acts as a natural breakwater for this area. The FWOP model runs indicated most of the damages in Ocean Park were from inundation, therefore breakwaters would not address the main damage driver and provide less benefits when compared to alternative measures. Additionally, Dean and Dalrymple (2002) point out that "… unless this type of structure is filled artificially to its capacity concurrent with construction, there will almost certainly be adverse effects on the adjacent shorelines (particularly on the downdrift side), for any sand they impound is taken from the littoral system." This indicates a breakwater or a field of breakwaters for the Rincón study area would need to be accompanied by sand nourishment (and likely a lot of sand) given the study area is critically eroded without the presence of an updrift feeder beach. Estimated adverse impacts to adjacent shorelines in this area and adding additional measures to accompany breakwaters for Rincón meant breakwaters were less beneficial than other measures discussed above. Breakwaters in both Ocean Park and Rincón would require a large footprint to provide benefits; therefore, increasing the costs and environmental impacts related to this measure. For these reasons, USACE screened breakwaters from additional analysis. For additional information and guidance on breakwaters reference EM 1110-2-1617 (USACE, 1992b) and EM 1110-2-1100 (USACE, 2008b).

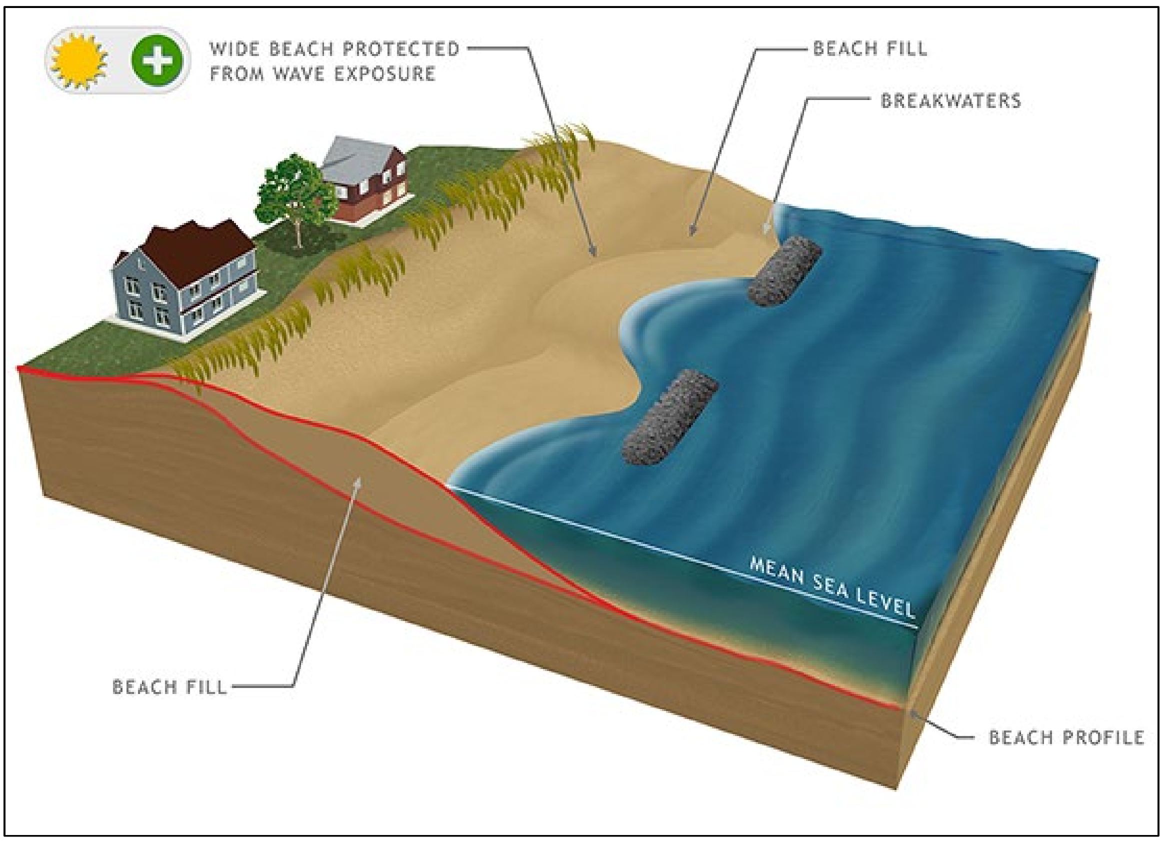


**Figure A-98. Breakwater CSRM Measure Example (USACE, 2015)**

## 4.6 Alternative Evaluation

After developing a better understanding of the storm-induced problems following FWOP model runs, both Beach-*fx* and G2CRM assessed an array of alternatives to determine the alternative that best addresses the study objective within the plan formulation process. FWOP modeled damages from both Beach-*fx* (first row of structures and contents) and G2CRM (remaining inland structures and contents) were seamlessly combined and reported in Appendix B: Economic Analysis. FWOP damages in Condado, Punta Piedrita, western Ocean Park, and central to eastern Isla Verde were extremely small compared to the other San Juan analysis areas. Low erosion in these areas (or no erosion predominately at the headlands where nearshore and shoreline hardbottom was present) mitigated erosion damages, larger and connected shoreline armoring such as existing seawalls and revetment diminished wave attack issues, and higher upland elevations and shoreline armoring greatly reduced inundation problems. Each alternative listed below includes a single or combination of management measures, listed in Section 4.5, and evaluated with the life-cycle planning models detailed in Section 4.

### *4.6.1 Ocean Park Planning Reach*

The Ocean Park Planning Reach experienced the most damages of any study area for this project. This was primarily due to low-lying inland elevations, critically eroded shorelines and higher erosion rates, and a lack of shoreline protection in front of inundation focal points like Barbosa Park and the Marías Skate Park which allow coastal waters to propagate inland and pool in the lowest elevated areas between the coastal-fronting shoreline and the San Jose Lagoon.

#### 4.6.1.1 Alternative 1 – No-Action

Alternative 1 is the no-action Plan, which represents the FWOP scenario. Figure A-99 displays the key problems within the Ocean Park Planning reach; with blue arrows designating the inundation focal points at Barbosa Park and the Marías Skate Park and orange arrows designating the areas where most erosion damages occurred. The Economics Appendix discusses detailed FWOP results. With no-action, coastal flooding, erosion, and wave attack will continue to place infrastructure and the public at risk during various storm events.

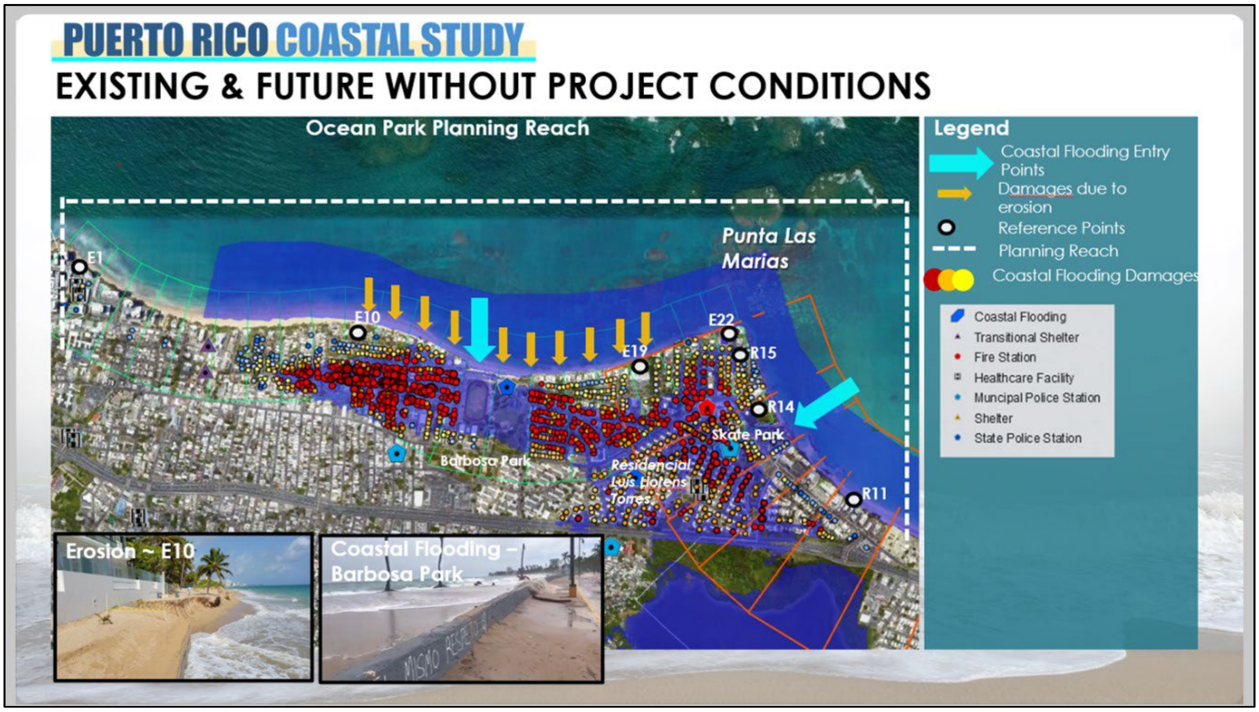


**Figure A-99. Problems in Ocean Park Planning Reach**

#### 4.6.1.2 Alternative 2 – Floodwall with Rock Armor (E13 to E15 and R14)

Alternative 2 consists of a floodwall with buried rock armor, displayed in Figure A-100. This alternative would reduce the risk of coastal flooding at the most critical locations: Barbosa Park and the Marías Skate Park. The walls also provide a secondary benefit of mitigating shoreline erosion and associated damages landward of the seawalls. The Barbosa Park floodwall is a steel sheet pile wall with a concrete cap and rock armor protection on the seaward side of the wall. Rock armor will provide protection to the structure toe by abating potential scour and reducing potential wave reflection. A marine mattress will serve as the underlayer bed for the rock armor and extent beyond the toe of the armor stone for additional stability. A small dune feature will be placed seaward of the wall to cover the rock armor and reduce potential adverse impacts to the coastal system. The western side of the Barbosa Park floodwall includes flood gates to provide access to the existing parcels. Additionally, the floodwall will require demolition of an existing roadway and sidewalk seaward of Barbosa Park, which will be replaced with beach-quality sand and the small dune feature. A replacement sidewalk would be constructed on the landward side of the floodwall and function as access for operation and maintenance purposes of the structure.


**Figure A-100. Ocean Park Alternative 2**

The Marías Skate Park floodwall is also a steel sheet pile wall with a concrete cap. Due to the floodwall's proximity to the water it will consist of a rock protection feature that is more robust than the Barbosa Park location with the intent to dissipate wave energy and provide scour protection. A marine mattress will serve as the underlayer bed for the rock armor and extent beyond the toe of the armor stone for additional stability. The rock armor at this location will not be covered by a dune feature. The alternative at this location will consist of demolition and removal of debris with replacement of sand for backfill up to the floodwall top elevation. Section 5.1 contains additional details on both the Barbosa and Marías Skate Park floodwalls.

Economic analyses within G2CRM determined the floodwall design elevation by comparing the net benefits of various elevations shown within Table A-39 and Figure A-101 to Figure A-102. An increase in the design elevation inherently increased the wall length, and therefore cost, due to the additional protection needed to tie-into the higher design elevations. Ultimately, the 7 feet PRVD02 design elevation produced the highest net benefits and therefore was carried forward for all alternatives. Additional details and typical cross-sections for both the Barbosa Park and the Marías Skate Park floodwalls are discussed in Section 5.1 and displayed in Figure A-116 and Figure A-117.

**Table A-39. Design Elevation Assessment**

| Elevation (ft PRVD02) | Benefits | Total Cost | Net-Benefits |
|---|---|---|---|
| 6 | $78,493,000 | $31,267,000 | $47,226,000 |
| 7 | $85,632,000 | $31,267,000 | $54,365,000 |
| 8 | $101,367,000 | $66,921,000 | $34,446,000 |

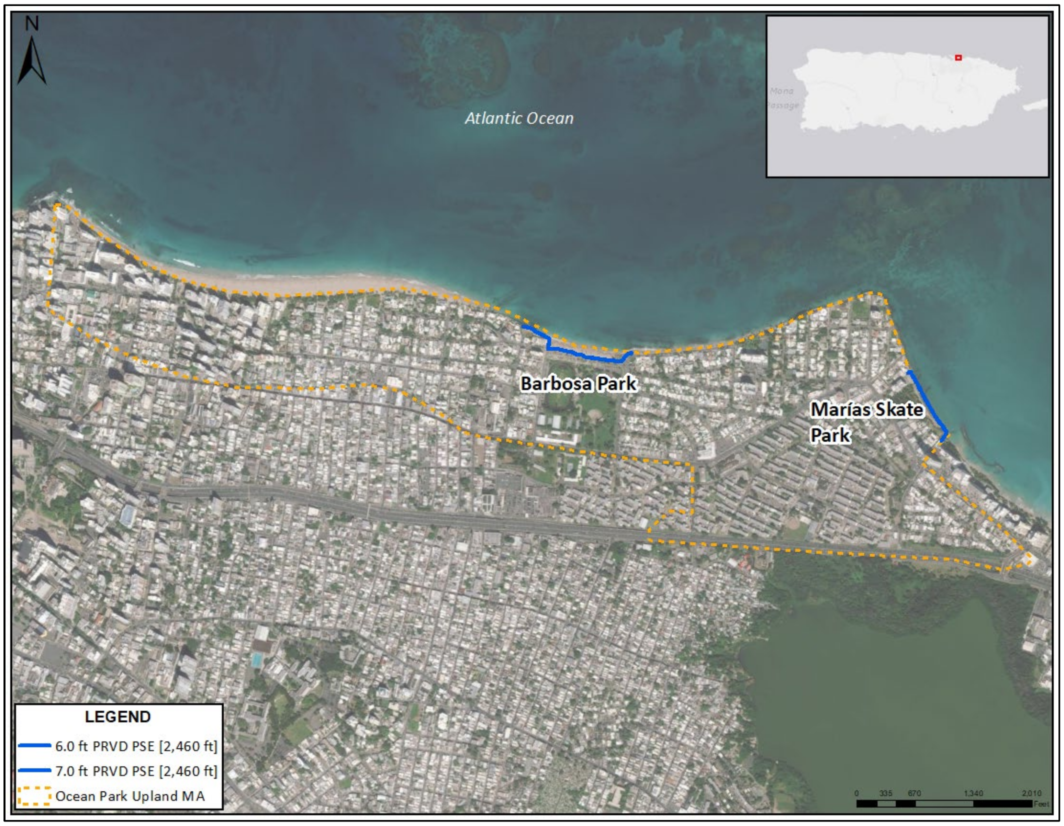


**Figure A-101. Design Elevation Assessment (6 to 7 feet PRVD02)**

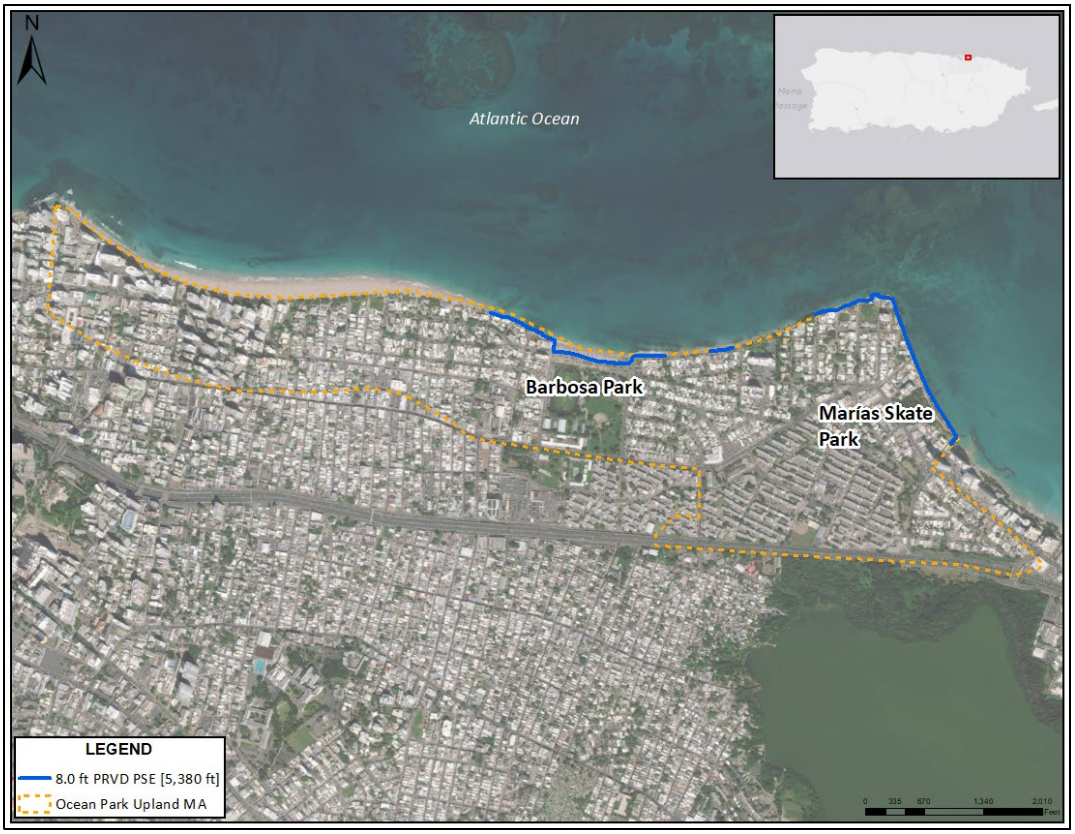


**Figure A-102. Design Elevation Assessment (8 feet PRVD02)**

4.6.1.3 Alternative 3 – Floodwall with Rock Armor (E13 to E15 and R14) Plus Beach Nourishment with Vegetated Dune (E10 to E19)

In addition to the 7 feet PRVD02 floodwalls described within Alternative 2 (for inundation protection), Alternative 3 includes a beach nourishment with vegetated dune that extends from Reach E10 to E19, as shown in Figure A-103. The intent of the beach nourishment and vegetated dune proposed is increased protection from erosion and wave attack damages incurred on the Beach-*fx* model reaches that experienced the most erosional damages. To determine the beach and dune dimensions Beach-*fx* compared over twenty combinations of beach and dune alternatives in the Ocean Park model reaches where the highest FWOP erosion damages occurred. USACE selected three beach and dune alternative combinations based on their ability to reduce damages equal to or greater than 75 percent and their cost effectiveness, shown in Table A-40. The beach and dune alternative that produced the highest net benefits, highlighted in green within Table A-40, was carried forward within Alternative 3. The beach nourishment will consist of one initial nourishment of approximately 415,000 cy and four periodic nourishments (occurring approximately every 12 years), each approximately 305,000 cy, throughout the 50-year period of Federal participation.


**Figure A-103. Ocean Park Alternative 3**

**Table A-40. Beach and Dune Dimension Assessment**

| Alternative | Incremental Benefits | Incremental Cost | Incremental BCR | Incremental Net Benefits |
|---|---|---|---|---|
| 10’ Berm, Dune 12’ high/20’wide, 5 yr | $27,152,000 | $136,401,000 | 0.20 | ($109,249,000) |
| 10’ Berm, Dune 12’ high/20’wide, 10 yr | $20,551,000 | $121,592,000 | 0.17 | ($101,041,000) |
| 20’ Berm, Dune 12’high/20’wide, 5 yr | $27,276,000 | $150,617,000 | 0.18 | ($123,341,000) |

#### 4.6.1.4 Alternative 4 – Floodwall with Rock Armor (E10 to E19 and R14)

Alternative 4 consists of a floodwall, at a design elevation of 7 feet PRVD02, similar to Alternative 2 except it would extend further to the west and east at the Barbosa Park location, see Figure A-104. This alternative was considered to determine if the combined protection of inundation, erosion, and wave attack damages would provide further justification than other alternatives that mostly protect the inundation focal points of the model reach. Therefore, in addition to the flood risk reduction previously described in Alternative 2, this alternative would provide erosion and wave attack protection to the infrastructure landward of the floodwall. Compared to Alternative 2, the floodwall will extend 0.45 miles to the west of Barbosa Park (from E10 to E13) and 0.30 miles to the east of Barbosa Park (from E15 to E19), with a total length of approximately 1.0 miles in Barbosa Park and 0.23 miles in the Marías Skate

Park. The floodwall within both Barbosa Park and the Marías Skate Park would match the design elevation described within Alternative 2 (7 feet PRVD02) and the floodwall/rock armor would generally consist of the same design parameters and dimensions previously described for Alternative 2. Within the locations west and east of Barbosa Park (E10 to E13 and E15 to E19) an initial fill placement for a construction pad would be included prior to construction to allow construction along the seaward side of the wall.


**Figure A-104. Ocean Park Alternative 4**

4.6.1.5 Alternative 5 – Floodwall with Rock Armor (E13 to E15 and R14) Plus the Acquisition of Structures and Property

Alternative 5 is the same as Alternative 2, but it includes acquisition of structures and properties at the western location of Barbosa Park, see Figure A-105. The floodwall would reduce the risk of inundation into the Ocean Park Planning Reach, while the structure acquisition will return the topography to its natural beach state. The floodwall within both Barbosa Park and the Marías Skate Park would match the design elevation described within Alternative 2 (7 feet PRVD02) and the floodwall/rock armor would consist of the same design parameters and dimensions previously described for Alternative 2. The structure acquisition would consist of seven structures on eight parcels located on the western side of Barbosa Park. The structures and property would be acquired, demolished, and backfilled with beach quality sand.


**Figure A-105. Ocean Park Alternative 5**

### *4.6.2 Rincón Planning Reach*

FWOP damages in Rincón resulted mainly from armor failure and subsequent erosion, but this area incurred relatively minor inundation damages. Therefore, the alternatives described below focused primarily on protecting the Rincón Planning Reach from coastal erosion and wave attack damages.

#### 4.6.2.1 Alternative 1 – No-Action

Alternative 1 is the no-action plan. Figure A-106 displays the key problems within the Ocean Park Planning reach; with orange arrows designate the uniform erosion damages across the entire planning reach. Detailed FWOP results are discussed within the Economics Appendix. With no-action, coastal flooding, erosion, and wave attack will continue to place infrastructure and the public at risk during various storm events.

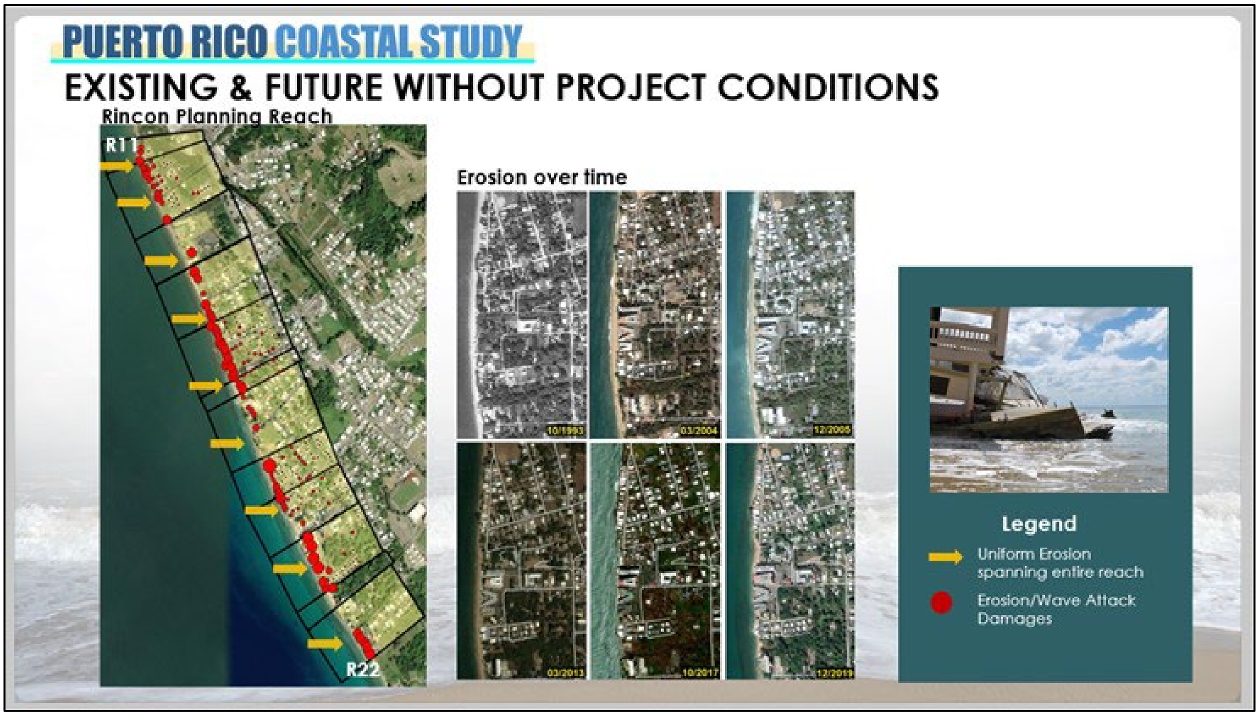


**Figure A-106. Problems in Rincón Planning Reach**

4.6.2.2 Alternative 2 – Revetment (R11 to R22)

Alternative 2 would consist of a rock revetment that runs along approximately 1.5 miles of shoreline, displayed within Figure A-107, with the intent to limit coastal erosion and reduce the infrastructures susceptibility to wave attack. Excavation of existing sand and rock to the appropriate grade is assumed, as well as initial fill placement for a construction pad to construct the project from the waterward side of the properties. A 1-foot marine mattress will serve as the foundation for the rock armor and extent beyond the toe of the armor stone for additional scour protection and stability. The armor stone would have a crest elevation of 11 feet PRVD02, crest width of 11 feet, and armor stones with an average weight ($W_{50}$) of 3-tons. The slopes of the revetment will consist of 1V:2H and 1V:3H on the landward and seaward sides, respectively. A typical cross-section of the alternative is displayed within Figure A-108.

The Puerto Rico Coastal Study considered revetments solely in the Rincón study area due to the desire to protect erosion damages experienced within FWOP modeling. Revetments are handled in Beach-*fx* by turning on armor across all reach upland lengths and allowing failure for each damage driver up to a specified threshold. USACE simulated this management measure to determine various design parameters associated with revetments and determine the design that produced the highest net benefits. Figure A-93 displays an example of a revetment.

**Figure A-107. Rincón Alternative 2**

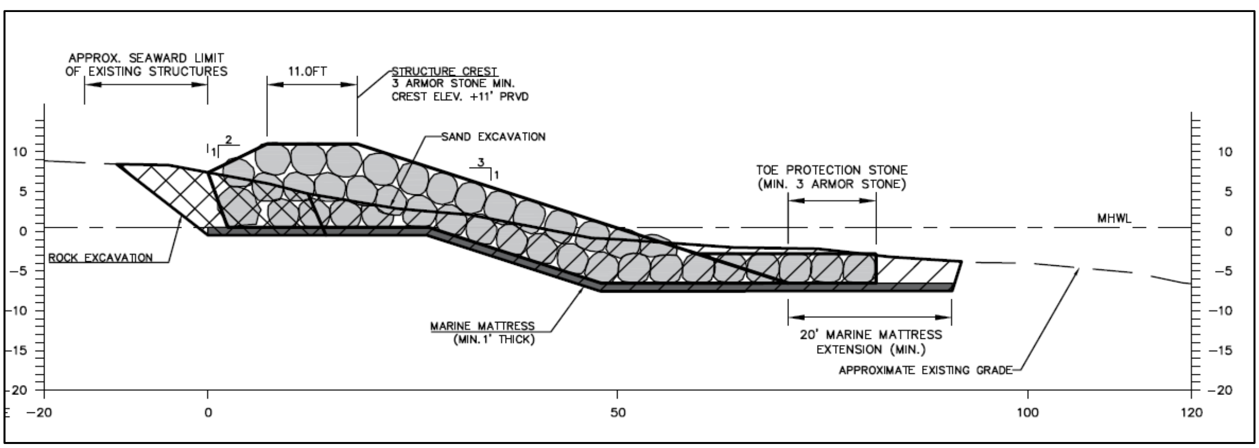


**Figure A-108. Typical Cross-Section of Revetment**

4.6.2.3 Alternative 3 – Beach Nourishment (R11 to R22) with Groins

Alternative 3 is beach nourishment with groins along approximately 1.5 miles of the coast, displayed in Figure A-109. Initially USACE had considered beach nourishment without groins; although, these alternatives were not economically justified due to lower BCRs. USACE selected three beach, dune, and groin alternative combinations based on their ability to reduce damages and overall cost effectiveness, shown in Table A-41. The beach and dune alternative that produced the highest net benefits highlighted in green within Table A-41, was carried forward within Alternative 3. The beach nourishment will consist of one initial and nine periodic nourishments throughout the 50-year period of Federal participation and each placement will consist of approximately 150,000 cy. The 12 groins proposed will generally extent approximately 50 feet seaward of the MHWL and have a total length of approximately 110 feet. The top elevation of the groins would be approximately 4 feet PRVD02. Excavation of existing sand and rock to the appropriate grade is assumed, as well as fill placement for a construction pad (i.e., the groins will likely be installed following beach restoration to allow “dry” construction along the seaward side of the existing properties). A 1-foot marine mattress will serve as the foundation for the rock armor and extent beyond the toe of the armor stone by a minimum of 20 feet for additional stability and scour protection. The armor stone crest elevation is 4 feet PRVD02 with an average stone weight ($W_{50}$) of 3-tons. The seaward slope of the groin will be 1V:2H. A typical cross-section of Alternative 3 is displayed in Figure A-110.

**Figure A-109. Rincón Alternative 3**

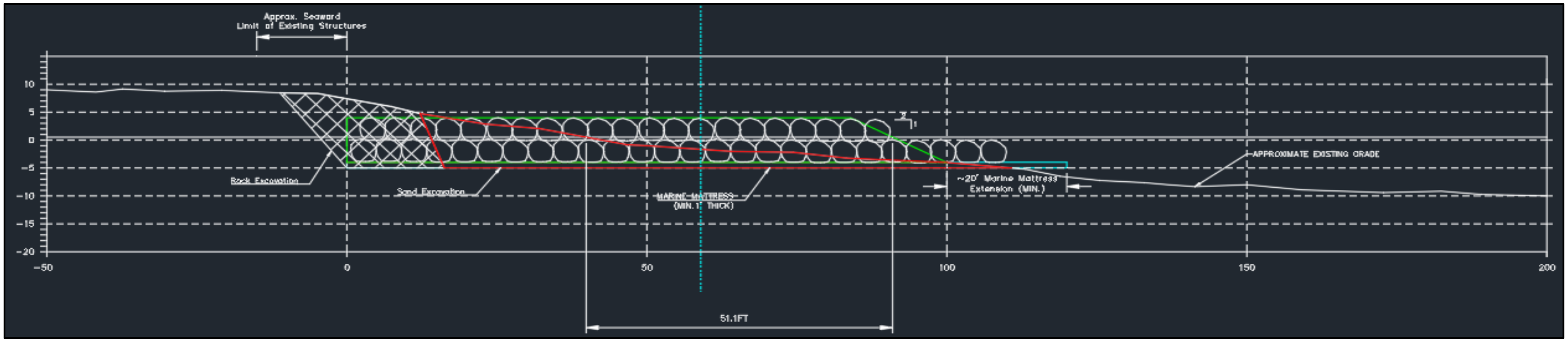


**Figure A-110. Typical Cross-Section of Groin**

**Table A-41. Rincón Beach and Dune Dimensions**

| **Beach Nourishment and Groin Alternatives** | | | |
|---|---|---|---|
| **Berm Width** | **Dune** | **Nourishment Period** | **Number of Groins** |
| 20-foot Berm | Existing Dune | 5 years | 12 |
| 10-foot Berm | Existing Dune | 5 years | 12 |
| 10-foot Berm | Existing Dune | 10 years | 12 |

#### 4.6.2.4 Alternative 4 – Acquisition (R11 to R19)

Alternative 4 consists of acquiring the most vulnerable structures and properties within the Rincón shoreline as displayed in Figure A-111. With this plan, high-risk structures along approximately 1.1 miles of shoreline would be included for acquisition and residents would be relocated. Approximately 60 parcels would be acquired and following demolition of the existing structures approximately 30,000 cy of sand fill would be placed to return the coastline to its natural state. Notably, the fill will remain within the existing property boundaries (not placed in the water) to ensure the areas do not include any depressions or low areas following structure demolition. USACE identified an acquisition plan based on numerous factors, including but not limited to, predicted structure damage(s) from planning models, their physical location in relation to the existing water line, potential impacts to natural coastal processes (at present and into the future), and environmental resources. In general, structures that are not setback from the shoreline have and will continue to experience increased damages and/or condemnation and were shown to have an adverse effect on the coastal system. These structures are recommended to be acquired in Alternative 4. The full list of parcels to be acquired is found in the Real Estate Appendix.

**Figure A-111. Rincón Alternative 4**

### 4.7 Tentatively Selected Plan Discussion

The combined results from the two economic life-cycle models indicate a TSP for the Condado and Isla Verde planning reaches is no-action. The TSP within Ocean Park is the alternative that reasonably maximizes the net NED benefits, which is Alternative 2. Ocean Park's Alternative 2 is focused shoreline armoring at the inundation focal points: Barbosa Park and the Marías Skate Park and is displayed within Figure A-100 and previously described in Section 4.6.1. The model results for the Rincón study area indicate no-action is the NED Plan, but analyses of all four P&G planning accounts show this area may be underrepresented by just the NED Plan. When considering the other P&G accounts for Rincón (environmental quality, regional economic development, and other social effects), the alternative that yielded the most holistic plan was Alternative 4. Rincón's Alternative 4 is to acquire the most vulnerable structures and properties in the Rincón study area, demolish these structures, and backfill the acquired land with beach quality sand as detailed in Section 4.6.2 and shown in Figure A-111. The TSP for both Ocean Park and Rincón is further described below within Section 5. The Economics Appendix further details economic analyses that result in NED benefits and overall BCRs.

In conjunction with the TSP, it is recommended the NFS pursue measures such as local outreach and evacuation plan/notification improvements. To maintain life safety, with or without the project, it is important that residents continue to understand evacuation plans, receive notification of evacuation orders, and follow evacuation orders. Additionally, acquiring structures and property should be accompanied by the local government establishing and enforcing a coastal regulatory program to regulate current and future coastal development. This could be modeled after the CCCL Program administered by the FDEP in Florida, which ensures the reasonable use of private property and protects the natural beaches and dunes.

# 5 PROJECT DESIGN

The TSP for the Puerto Rico Coastal Study includes no-action in Condado and Isla Verde, floodwall construction along two low-lying shorelines in the Ocean Park project area (Barbosa Park and Marías Skate Park shorelines), and acquiring the most vulnerable structures and property in the Rincón project area. This section of the report provides engineering design details, additional engineering considerations including risks and uncertainties, and an outline for future PED phase services for the TSP.

## 5.1 San Juan Planning Area TSP General Description

The TSP for the San Juan area includes floodwall construction along two low-lying areas – Barbosa Park and along the eastern portion of Punta Las Marías. The intent of the walls is to reduce the large-scale flooding from coastal storms predicted to compound in the low-lying interior areas of San Juan. The walls also provide a secondary benefit of mitigating shoreline erosion and associated damages landward of the seawalls.

The proposed floodwall in the Barbosa Park area is in the general vicinity of the eastbound lane of Park Boulevard. The proposed TSP includes removal of the existing roadway and sidewalks along the northern portion of Barbosa Park and installing the wall within the landward portion of the existing roadway (Park Blvd). Utilities within the existing road footprint will be relocated landward of the proposed wall alignment and a new sidewalk (like the existing sidewalk) will be constructed immediately landward of the wall. The removed roadway and sidewalk infrastructure will be replaced with beach-quality sand and a small dune feature (approximately 12,000 cy total) to provide increased recreational beach area and reduce the potential for adverse impacts to the coastal system from the wall. The dune feature will provide approximately 3 feet of cover above the rock armor. The sand placement is not anticipated to impact nearshore resources due to the placement location along the upper beach area and the small volume of sediment. The sidewalk along the landward side of the proposed wall will provide similar recreation opportunities and connectivity as the existing sidewalk, however, will be set back further landward from the increased beach area. The two parking areas along the northern limit of Barbosa Park will remain and additional accesses to those parking areas will be provided from the adjacent streets (Calle Coldado Serrano and Av. Las Americas).

The wall will tie-in with higher elevation topography and/or existing structures meeting the intended design elevation (7 feet PRVD02) along the eastern limit of Barbosa Park, near the existing rock and seawall fronting Park Blvd. West of Barbosa Park, the wall will run along the northern road right of way of Calle Espana and the eastern road right of way of Calle Rampla del Almte. The preliminary wall alignment is along the edge of the road right of way in the vicinity of the existing sidewalks, immediately adjacent to the current private property. The wall will include removable flood gates to provide access to the existing parcels (two per parcel, similar number of accesses to existing conditions) and are anticipated to generally consist of engineered planks that will slide and lock into a structural anchor (jamb) on either side of the wall. The removable flood gates are currently proposed to be approximately 15 feet wide x 4 feet high and will only be installed during major storm events. The NFS will be responsible for deploying/operating the flood gates, as discussed in Section 5.1.4.1. Final engineering designs and details will be determined during PED.

The floodwall along the east side of Punta Las Marías is primarily within the Parque de Patinetas de Punta Las Marías (Marías Skate Park) with return wall extensions to the north and south tying into existing upland areas meeting the intended design elevation of approximately 7 feet PRVD02. The wall is currently proposed to be placed immediately seaward of the existing concrete seawall along the waterfront properties and will extend north to Calle Inga and south to encompass the small public accessway.

Figure A-100, Figure A-112, and Figure A-113 provide a general location map and approximate alignment of the proposed walls. Both walls are designed with a crest height of approximately 7 feet PRVD. Both walls include an engineered foundation to reduce settlement, inhibit scour and foundation failure, and rock armor protection to reduce reflected wave energy. USACE also included project features in the preliminary design to maintain accessibility for Operations, Maintenance, Repair, Replacement, and Rehabilitation (OMRR&R) and inherently maintain existing public access. These features will be further refined during the PED phase of the project. Additional details for each project component are provided below.

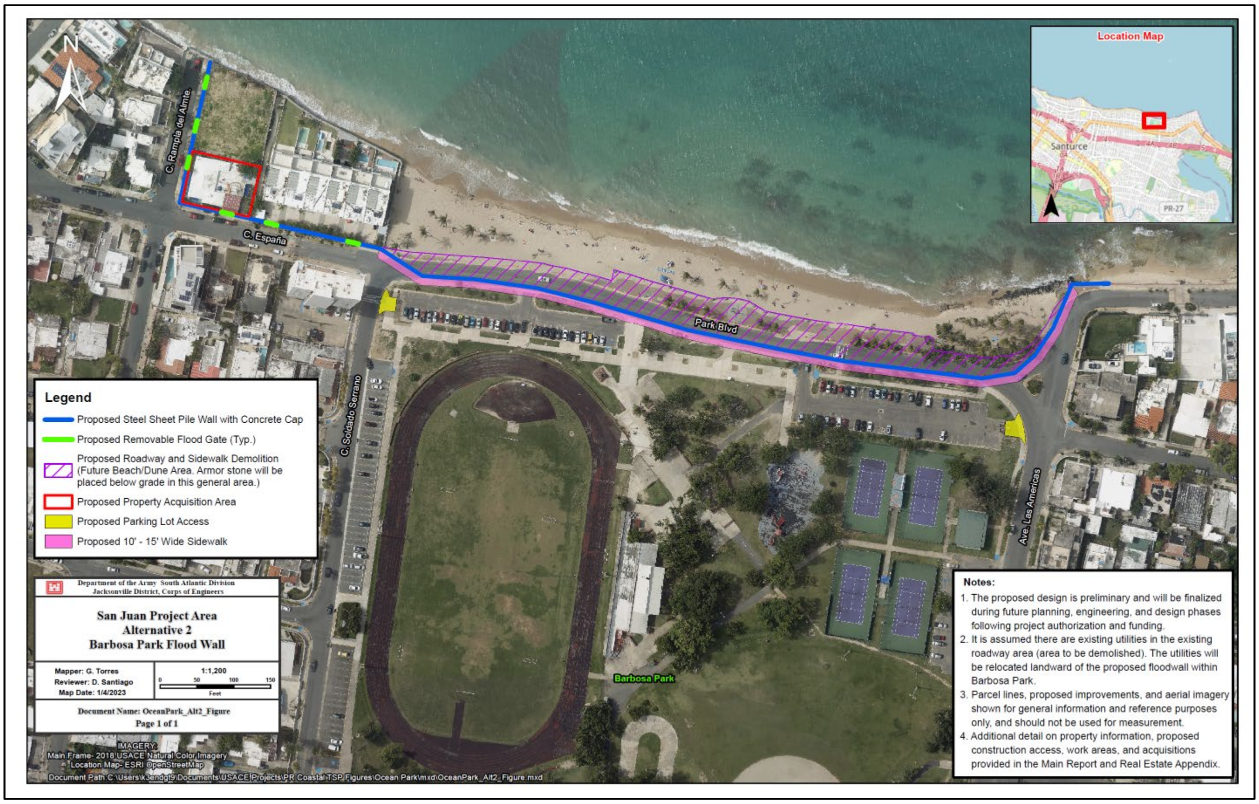


**Figure A-112. Proposed San Juan Project Area – Alternative 2 (Barbosa Park) Floodwall**

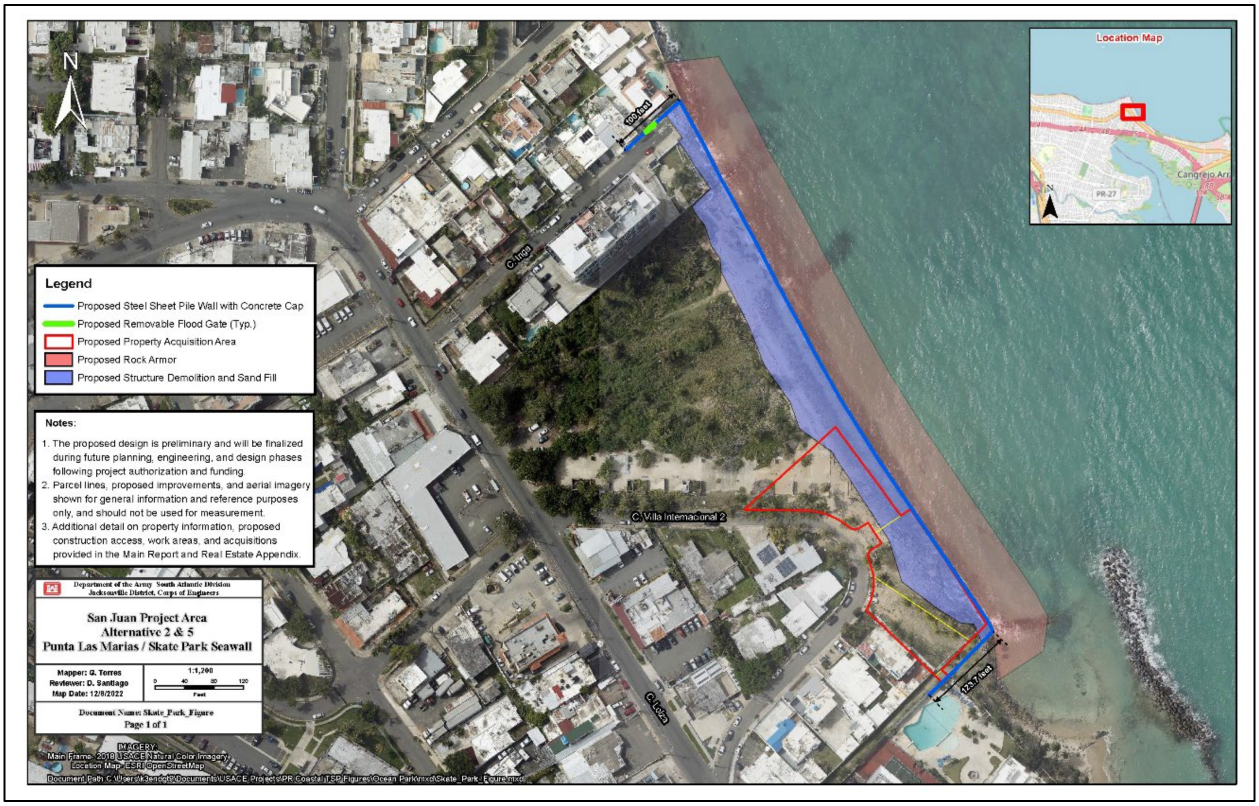


**Figure A-113. Proposed San Juan Project Area – Alternative 2 (Marías Skate Park) Floodwall**

### *5.1.1 Geotechnical Engineering*

A geotechnical site investigation (e.g., core borings, standard penetration tests, etc.) is not available for the proposed seawalls or other structures, and no testing or analysis was performed as part of this study. Estimated geotechnical soil parameters are provided for the preliminary design of the seawall based on the review of the geologic map below and the information provided in the Geotechnical Appendix (Appendix B). A site-specific geotechnical investigation is required for the final design of the seawall and the assumed parameters will be finalized once additional boring data are provided for the final wall alignment. Additional geotechnical investigations will likely be required at each of the flood gate locations if flood gates are proposed in the final wall design.

As indicated in the geotechnical appendix, the beach composite sample for San Juan Beaches was classified as clean, poorly-graded, fine-grained quartz sand (SP) with a mean grain size of or 0.21 mm, and a standard deviation of 0.86 phi. The average percentage of fines passing the #230 sieve is 2.29. The average visual shell percentage is 20 %, with a range from 8.7 % through 43.8 %. The typical moist Munsell Color value is 6 and color is described as light brownish gray.

The geologic map of San Juan, PR indicates the site lay within Beach Deposits (Qb , Holocene) Formation which is composed of sand grains of quartz, volcanic rock, and shell. Eolianite bedrock is also common within the project area. The bedrock is from the Quaternary period (Holocene and Pleistocene epoch) and is composed mainly from calcareous sandstone, well-cemented, crossbedded, and composed of fine to coarse grains of shell fragments and quartz. Beach deposits atop the bedrock vary significantly but are generally between 1 to 20 feet thick. Below the sand layer, an Eolianite bedrock is encountered to a maximum thickness of 100 feet. Table A-42 includes the preliminary soil parameters estimated for the floodwall design. These parameters will be finalized following additional site investigations for the floodwall design.


**Figure A-114. Geologic Map of San Juan, Puerto Rico in 1977**

**Table A-42. Preliminary Soil Parameters for Floodwall Design**

| Material | Saturated Unit Weight (pcf) | Moist Unit Weight (pcf) | Friction Angle (ϕ') | Cohesion (C', psf) | Coefficient of Horizontal Subgrade Reaction (k) Above Groundwater (pci) | Coefficient of Horizontal Subgrade Reaction (k) Below Groundwater (pci) | $K_{rm}$ | $E_{rm}$ (psi) |
|---|---|---|---|---|---|---|---|---|
| Beach Deposits (SP, SP-SM) | 100 | 95 | 28 | 0 | 4 | 2 | - | - |
| Sandstone (Eolianite) | 150 | 145 | 30[(1)] | 7,200[(1)] | - | - | 0.000275 | 319,500 |

[1]Values estimated for rock mass.

### *5.1.2 Structural Engineering*

For the TSP, USACE performed preliminary, feasibility-level design analyses for the proposed walls. Numerous wall designs were initially considered, such as concrete panels and T-walls. Given the proposed location along the coast and presence of the varying elevation bedrock and existing structures, a steel sheet pile wall was considered the preferred floodwall structure. The sheet pile wall can be installed along the coastline in front of existing structures or along the upland within a relatively small footprint and can provide flood protection up to the design cap elevation. The sheet pile wall can also protect and retain upland soils/property from erosion and wave attack. Alternative wall materials will likely be investigated in PED.

The preliminary design process considered varying wall heights ranging from 6.0 to 8.5 feet PRVD02, however, economic analyses within G2CRM determined the final cap elevation by comparing the net benefits of various elevations. For each of the varying flood conditions (water level elevations) analyzed, the modeling team determined the general location and alignment of the walls based on the existing topography and existing structures. The 2018 USACE LiDAR data provided general elevations for the upland, beach, nearshore and offshore areas to support the preliminary design. For each of the flood elevations considered, the proposed floodwalls were extended laterally along the coastline or upland areas such that they tied into existing topography and/or structures that exceeded the design elevation with reasonable assurance. Notably, the walls immediately west of Barbosa Park may not be necessary as those properties currently include seawalls along the seaward edge of the property that, from visual observations, appear to meet the required design elevation. However, the structural condition of those walls is unknown, and should they fail, the upland topography data did not include sufficient detail to provide reasonable assurance the upland elevations would provide the necessary flood protection. As such, USACE extended the feasibility-level floodwall alignment to encompass these properties. Notably, an initial design proposed aligning the floodwall along the seaward edge of the properties west of Barbosa Park (immediately west of the existing seawalls and/or coastal armoring). However, considering the construction and maintenance access difficulties and the relatively large footprint of the required rock armor protection and potential adverse impacts to the coastal system, USACE recommends placing the wall in the current alignment.

For the Barbosa Park area, the proposed floodwall generally runs along the eastbound (landward) lane of Park Boulevard and ties in with higher elevation topography and/or existing structures meeting the intended design elevation along the eastern limit of Barbosa Park. West of Barbosa Park, the wall will generally run along the landward edge of the private properties. While the general coastline area currently includes vertical seawalls with varying levels of rock armor protection with little to no dry beach, the proposed wall locations have been shifted landward to reduce the potential adverse erosion impacts associated with vertical-face walls on open coasts. Additionally, the proposed walls include robust rock armor on the seaward side of the wall where the walls are exposed to direct wave attack (discussed in further detail below). Should the wall become exposed to open coast conditions in the future (surge and direct wave impact), the rock armor will dissipate incident wave energy and greatly reduce the reflected wave energy that is currently increasing erosion in the general project area. Additionally, the rock armor along the Barbosa Park area is proposed to be placed below existing grade and will be buried under a small dune feature to reduce potential adverse effects to the coastal system. Notably, the currently proposed alignment and design represents the maximum wall length and footprint for the floodwall and rock armor. Additional detailed analyses performed during the PED phase (discussed further below) may show the existing structures provide suitable elevations negating the need for a wall west of Barbosa Park. Regardless, public access to Barbosa Park and the beaches seaward of the Barbosa Park wall will be maintained.

For the Marías Skate Park area, the proposed floodwall generally runs immediately seaward of the existing concrete seawall. This alignment will protect the upland area from the design flood conditions and storm-induced erosion. The Marías Skate Park floodwall is proposed to connect to an existing seawall to the north (near the end of Calle Inga) or include a short return wall north of the road (the current design assumes a short return wall into the uplands). At the south end, the wall will include an upland return wall between the public alleyway and the private property to the south, displayed within Figure A-113. The final design will include a flood gate, overwalk, or other similar structure that will allow pedestrian access while also inhibiting flood waters during major storm events.

The preliminary structural analysis considered usual, unusual, and extreme design conditions. The usual cases included normal operating conditions at MHHW and mean lower low water levels. The unusual cases included an operational basis earthquake event at mean water level and a construction (increased upland loading) condition at mean lower low water. The extreme case included a maximum design earthquake event at the mean water elevation. The design process considered combinations of each of these parameters to determine the controlling conditions.

The floodwall design also considered the difficulty in driving sheet pile walls within the coastal environment and the dense sandstone/bedrock likely to be encountered. A thicker section was selected to account for the increased forces required to drive the sheet pile into the dense sandstone/bedrock. Lastly, given the limited accessibility of the wall following construction, the wall design assumed a 50-year design life and included additional wall thickness to account for the anticipated corrosion in a marine/coastal environment.

#### 5.1.2.1 Floodwall Design

The current preliminary wall design includes a cantilevered NZ-22 steel sheet pile wall section, grade 60, with a crest elevation of approximately 7.0 feet PRVD02 driven to a penetration depth to approximately -23 feet PRVD02. The overall length of the sheet pile wall would be approximately 30 feet. The wall will be coated with coal-tar-epoxy on both sides and 10 feet below the resisting side ground for additional corrosion protection and will include an approximate 3-foot by 3-foot concrete cap atop the wall. The design also includes a small volume of beach quality fill (~7,000 cy) in the Barbosa Park area to be used for backfilling, if needed, and a larger volume of backfill (~10,000 cy) for construction access in the Marías Skate Park area. A small dune feature (~5,000 cy) will provide approximately 3 feet of cover above the rock armor. Figure A-115 below provides a general cross-section of the proposed floodwall. Additional design details and assumptions are provided below in Section 5.1.3.

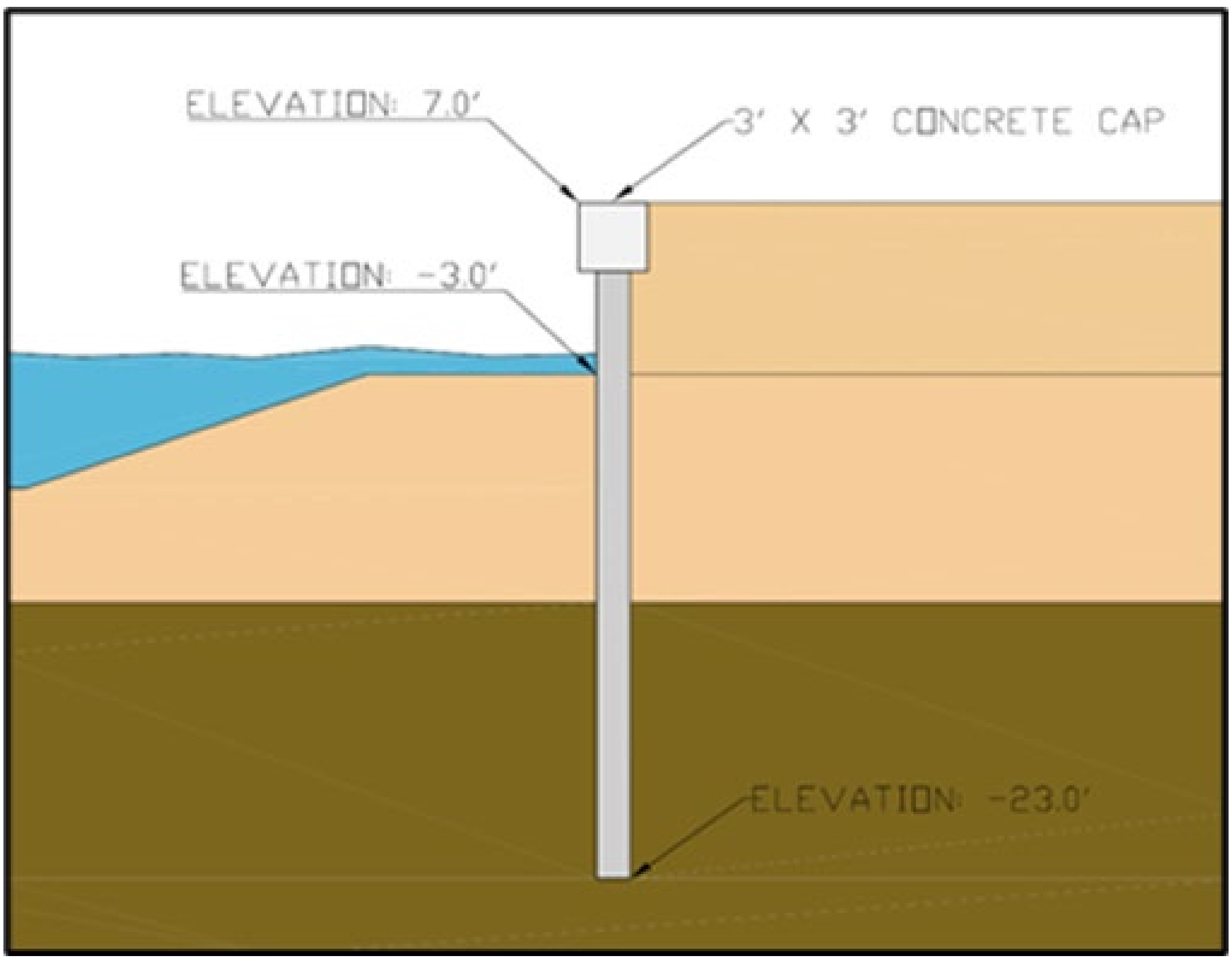


**Figure A-115. Preliminary Sheet Pile Wall Cross-Section (Rip rap not shown for clarity)**

#### 5.1.2.2 Rock Revetment Design

Portions of the wall will be placed along the open coast and subject to large, dynamic coastal forcing from waves and storm surge. To reduce the impact loading and wave reflection off the wall, the proposed design includes an engineered foundation and armor stones along the seaward side of the wall. An engineered foundation, such as a marine mattress, will reduce the potential for scour and erosion, as well as settlement of the proposed armor stones. The armor stones on the seaward side of the wall will reduce incident and reflected wave energy through wave breaking/dissipation (and potential adverse effects associated with reflected wave energy), likely reduce overtopping into the upland areas, and provide added support to the floodwall. Of note, smaller-scale armor and toe protection was initially considered, however, was deemed insufficient along the high-energy, open-coast project areas. The rock armoring may be reduced (both the size of the stone and overall footprint) during the PED phase following detailed geotechnical investigations, however, the design should also consider the future conditions in each specific project area over the proposed 50-year design life (i.e., while the wall may not be exposed to severe conditions currently, it may be exposed to those conditions in the future).

Given the currently proposed wall locations along a densely developed, open-coast shoreline, any maintenance or repair of the structure in the future will be very difficult and costly. As such, the foundation and rock armor design primarily focused on severe storm events that may impact the area. In addition, the foundation will be excavated into the existing bottom to reduce foundation failure and/or settlement. The proposed rock armor design consists of the following:

- Crest Elevation: ~5 feet PRVD02 at Barbosa Park and ~7 feet PRVD02 at the Marías Skate Park
- Crest Width: 12 to 14 feet (3 armor stones wide)
- Side Slopes: 3H:1V
- Stone Size: 5 to 7 ton (approximately 4.5- to 5.0-foot diameter stone)
- Stone Unit Weight: 160 lbs/ft$^3$ or greater

Figure A-116 and Figure A-117 below provide typical cross-sections of the proposed floodwall including the engineered foundation and rock armor for both the Barbosa Park and Marías Skate Park project areas. The preliminary design includes a relatively wide crest and a mild slope (1V:3H) to provide increased wave energy reduction, reduced wave reflection, reduce the required stone size, and to match the existing beach grade more closely to the east and west. Further, from the NFS and other local input, gradually sloping structures are typically preferred over vertical or steep-faced structures. As previously noted, these designs are preliminary and will be refined during the PED phase following detailed data collection and further engineering analyses.

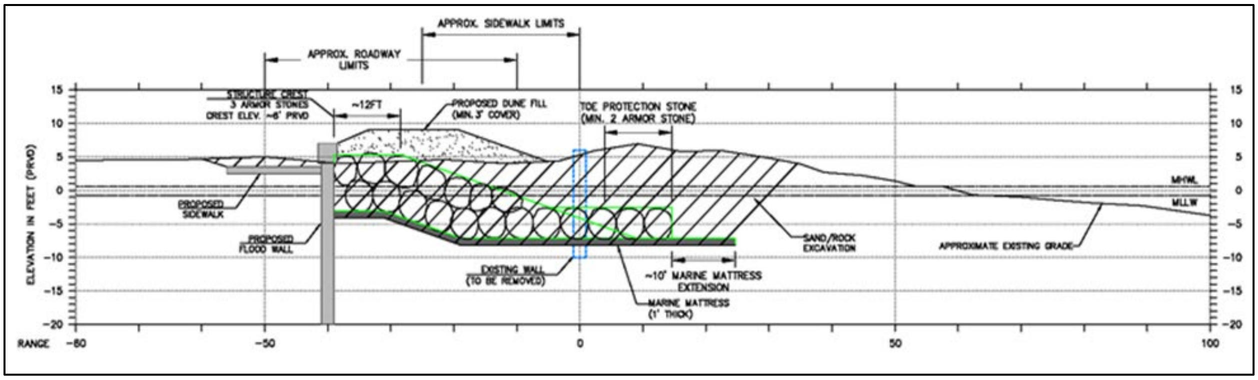


**Figure A-116. Typical Floodwall and Rock Armor Protection along Barbosa Park**

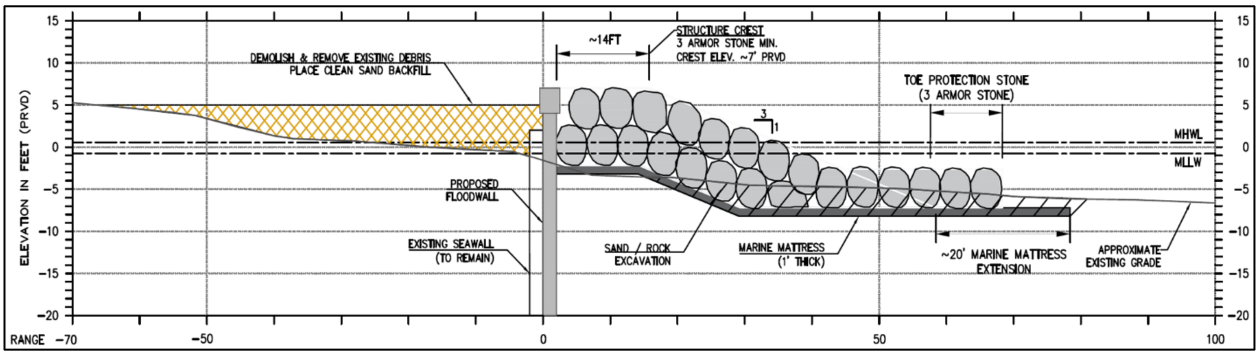


**Figure A-117. Typical Floodwall and Rock Armor Protection along the Marías Skate Park**

### *5.1.3 Additional Engineering Considerations*

The following section provides additional engineering considerations for the selected plan, including additional design assumptions, constructability and access risks, and uncertainties. These are provided to understand the assumptions and risks of the TSP and to identify additional potential measures that may be necessary to mitigate these risks during future design efforts.

#### 5.1.3.1 Design Assumptions, Constructability and Access Risks and Uncertainties

The proposed San Juan area TSP presents numerous construction challenges. The challenges as well as the approach to reducing the risk associated with these challenges is summarized below.

Construction Access: The preliminary design and cost estimate assumes construction will be land-based. For Barbosa Park, construction staging and access will likely be provided within the park. The design assumes a small quantity of fill will be brought in to provide a construction “pad” to walk equipment along the eastern wall section if necessary. The volume of fill may need to be increased depending on the conditions along Barbosa Park and the adjacent areas at the time of construction, however, this is a relatively small cost item compared to the overall project. For the wall west of Barbosa Park, the design and cost estimate assume construction will generally occur within the public road and a small area immediately on the adjacent private property (an approximately 20-foot-wide construction easement). Notably, the TSP assumes the property on the corner of Calle Espana and Calle Rampla del Almte (inside the red polygon in Figure A-112) will be acquired as the structure will likely be impacted during construction. For the Marías Skate Park area, construction access and staging will be provided through proposed parcel acquisition (three southernmost, undeveloped parcels of the project area), and through additional temporary construction easements along the upland private properties, shown in Figure A-113. The Marías Skate Park design assumes the existing (currently exposed) building foundation will be demolished and approximately 10,000 cy of clean backfill will be brought in to raise the area immediately landward for construction operations. Additional details on the parcel acquisition and construction easements are provided in the Real Estate Appendix.

Sheet Pile Wall Installation: The design assumes installation of the steel sheet pile wall into the relatively dense, existing bedrock. The sheet pile wall design assumes a larger steel section to withstand the increased driving forces into bedrock, however, the design and cost estimate also assumes the rock will be pre-drilled (prior to sheet installation) to account for the dense underlying material. Given the proximity to adjacent structures and driving the sheets into hard bedrock, excessive vibrations and noise to adjacent buildings and structures is a concern. As such, the current cost estimate assumes sheets will be driven using a "vibration free" methodology such as a hydraulic press to reduce these potential adverse effects. Regardless of the methodology, a pre-construction structural survey and noise/vibration monitoring program is recommended during construction to mitigate any unforeseen risks.

Existing Structure Demolition and/or Excavation: Aside from the small beach area of Barbosa Park, most of the project area includes existing vertical walls of varying size and materials. In addition, some of these walls include a wide array of armoring fronting the walls, consisting primarily of repurposed concrete and/or rock. Given the unknown condition of the existing structures, the preliminary sheet pile wall design assumes the proposed floodwall will receive no additional support from the existing walls. Additionally, the cost estimate assumes a small volume of excavation to remove the existing armoring fronting the walls in the project area and a small volume of backfill between the proposed floodwall and the existing walls. As mentioned above, the Marías Skate Park design assumes a larger volume of excavation to remove the existing foundation materials along the upland (removed to existing grade and capped with clean backfill).

Material Sourcing: Local mines/suppliers confirmed that beach quality sand and armor stone is available on the island and can be produced as requested. The steel sheet piles will likely be sourced from the states.

Environmental Impacts: The current design will likely have minor environmental impacts, primarily for the work occurring within the water. The proposed design represents a conservative (i.e., largest footprint) scenario and ideally will be scaled back during PED. In addition, the design assumes utilizing beach-quality sand and natural stone to replicate the existing habitats as close as practical within the engineering limitations. Additional details on the potential environmental impacts and proposed mitigation measures are provided in the Environmental Appendix.

Life Safety Risks: The USACE, SAJ Risk Cadre have completed a qualitative risk assessment for a portion of the Puerto Rico Coastal Study and a summary of the assessment is presented in Section 6.

#### *5.1.4 Pre-Construction, Engineering, and Design Phase Considerations*

The following section outlines considerations for PED-level data collection and design work to further address the remaining engineering design risks and uncertainties. While these considerations will be used to detail specific scopes of work to reduce risk during the PED phase, these items also present many areas to further "value engineer" the project to provide a more cost-effective and resilient design.

Site-Specific Survey Data Collection: While the 2018 USACE LiDAR data provides good coverage of the project areas, the data is somewhat limited (providing insufficient finer detail) in the narrow project areas where floodwalls are proposed. As such, USACE took a conservative approach to extend the proposed floodwall alignments to areas that provide reasonable assurance on the upland elevations and/or the condition of existing structures. Future PED phase will include detailed surveys (topographic, bathymetric, etc.) in the vicinity of all proposed improvements and work areas to refine the actual wall alignment and specific tie-in locations.

Geotechnical Conditions: The geotechnical conditions within the project area are likely challenging and will have a significant effect on the final design. The design team has taken a relatively conservative approach assuming the difficult conditions summarized above. During PED, a detailed geotechnical sampling and testing program will be developed and implemented to clearly identify the subsurface conditions prior to final design. The geotechnical appendix provides a preliminary summary of PED-level analyses proposed.

Utility Surveys: The proposed design included a preliminary review of known utilities in the proposed project area; however, unknown utilities may exist. Utility surveys will be performed during PED to document the presence of existing utilities that may affect the proposed design and/or need to be relocated.

Structural Condition of Existing Walls and Structures: The proposed floodwall alignment extends to adjacent areas where the existing topography reduces the potential for flooding; however, some areas where the walls will terminate are in the vicinity of existing structures. While the proposed floodwall design assumes no additional support from the existing walls, a structural survey shall be performed in PED where the proposed walls are tying in or abutting existing structures to document the condition of these structures prior to final design. Within PED, if existing walls and structures are determined to be structurally sound and have an elevation at or above the design elevation the structure alignment could be modified.

Hydraulic Modeling: During the PED phase, hydrology and hydraulics (H&H) may perform high fidelity modeling to confirm the flood paths and flood extents affecting the study area. This hydraulic modeling coupled with additional survey data would assist in the optimization of the design elevation to satisfy the feasibility-level recommendations, as well as potential refinements to the feature's tie in locations to existing grades. If additional flood paths through roadway extents are discovered with the high-fidelity modeling emergency deployable barriers (EDBs) and/or flood gates should be considered. Additionally, H&H could conduct an infra-gravity wave assessment to reduce the risk of adverse impacts to the design.

Inland Hydrology Analysis Refinement: It should be noted that if activities such as development of a storm water management plan, install, upgrade or improve rainfall runoff pumping facilities, establishment of an emergency protocol or operation of flood control features, detailed H&H studies, etc. within the project area are designed and permitted before or during PED activities, USACE will consider these improvements and incorporate them into the proposed project features to the best extent practicable. During the PED phase, H&H may complete an interior drainage analysis to design measures more accurately for interior drainage relief and to ensure the design does not exacerbate upland inundation. The analysis would entail the use of the HEC-Hydrologic Modeling System and HEC-RAS or the latest model available with the guidance of Engineering Manual 1110-2-1413. USACE would likely use rainfall frequencies ranging from the 50 percent to 0.2 percent AEP events with 24-hour point rainfall from NOAA Atlas 14 as the input alongside updated survey and alignment information. Additionally, currently no known stage or flow gauge information is in the project area. A deployment of such gauges would allow calibration of the Hydrologic Modeling System and/or RAS model to be completed, therefore providing a more accurate estimate of the appropriate design required for inland drainage.

Design Modifications: The proposed design assumes a typical sheet pile wall design throughout the entire project area. Following the PED-phase data collection mentioned above, the final wall alignment and general design will likely be modified. For example, should extended return walls be required at either project area, the design section or embedment depth for these walls may be reduced given the reduced loads in those areas. Geotechnical conditions may also allow alternative wall designs such as a reinforced concrete or gravity walls in certain areas. Additionally, it is recommended to further analyze the wave conditions adjacent to the project area to potentially refine the rock armor protection. The rock armor apron width and height may be subject to change following this analysis as well. If possible, modifications of the proposed armor and foundation system should be considered to reduce potential adverse impacts to the natural beach processes (e.g., cross-shore and longshore sand transport). USACE will reevaluate the crest elevation of the system to consider the latest information on the total water level, waves, tides, and SLC per the ER 1105-2-101 guidance on risk-based design. Additional load cases for the varying wall sections will also be considered in the PED-phase.

Design Life and Adaptability: The preliminary sheet pile wall and concrete cap design assume a design life of 50 years. At the end of the 50-year period of Federal participation, USACE assumes the project will be replaced and/or reassessed through a reauthorization process. During PED, it is recommended to investigate refined wall alternatives and materials to potentially extend the design life and reduce future maintenance costs. Adaptability of the wall is further discussed in Section 7.

Marías Skate Park Building Foundation: According to locals, a condominium was under construction and later abandoned many years ago within the Marías Skate Park property. Remnants of the building foundation remain on the site today, including a concrete seawall, concrete and steel pilings, concrete pile caps, etc. A brief records search for the structure did not uncover any details. During PED, additional information from the NFS should be requested regarding existing building construction files for details on the existing site features prior to final design to ensure these features will not adversely affect construction.

Barbosa Park Structures/Debris: Like the item above, existing structures and/or debris are along the west end of the Barbosa Park beach area that should be further investigated. The design and cost estimate assumes a small amount of demolition and removal, however, the volume and extent of this material remains unknown.

Public Access, EDBs and/or Flood Gates: The proposed walls will need to include public accesses through and/or over the wall for beach access in the vicinity of Barbosa Park. A public access gate will also need to be incorporated into the project along the south side of the Marías Skate Park (at the existing alleyway) and possibly at the north end to provide public access for fishing and other similar activities that typically occur in this area. In the area of the Marías Skate Park alleyway (and possibly other road ends where minor flood waters enter the San Juan area), the use of EDBs and/or other removable flood gates may provide a cost-effective approach to reducing flood inundation while also allowing access. The flood gates proposed for the wall immediately west of Barbosa Park abutting the private property will include a removable flood barrier. The flood gates generally consist of engineered planks that will slide and lock into a structural anchor (jamb) on either side of the wall. Each of these components will be reviewed in detail and final engineering designs prepared during PED.

Public Access, Recreation and Environmental Improvements: In addition to the wall alignment and design modifications presented above, additional opportunities for access, recreation, and environmental improvements may be in the general vicinity of the walls, both upland and offshore. These may include native plantings on the beach, increased accesses, and enhanced sidewalks and connectivity along Barbosa Park. Additional recreation and environmental enhancement areas may also be provided landward of the Marías Skate Park wall in the vicinity of the existing (dilapidated) building foundation, however, this will be dependent upon upland ownership.

Significant Changes to the Project Area, Existing Shoreline and/or Design Conditions: The preliminary design assumes the general project area conditions will be relatively similar to the existing conditions. The design may require modifications should the general project conditions change. For example, a major storm impacting the area resulting in significantly changed shoreline conditions, or a major development project in the project area that limits construction access.

Alignment and Easements: During the PED Phase, more information and data will be collected, including real estate information. Potential real estate requirements for the study area consist of fees, temporary and permanent work area easements, and road easements. These easements are necessary to provide adequate construction access, staging and work areas to build the proposed coastal storm risk management features and secure lands needed for operations and maintenance. Access and staging areas are assumed to be provided through the existing public lands and acquired property at Barbosa Park and through acquired property in the vicinity of the Marías Skate Park, however, these areas continue to be refined. The exact acreage and location will be refined in PED. More information on easements and real estate requirements can be found in the Real Estate Appendix.

Operation, Maintenance, Repair, Replacement, and Rehabilitation (OMRR&R): During the PED phase, the monitoring procedures for the project will be written in the OMRR&R Manual for the NFS, who will have the primary responsibility for operating and maintaining the project. A detailed summary of the potential OMRR&R is provided below.

Emergency Action Plan (EAP): Within the PED phase USACE will work with the NFS to complete an EAP. The EAP will need to specify thresholds to determine when flood gate closures take place and the duration that they will remain closed.

#### 5.1.4.1 Monitoring and Maintenance

The NFS should be prepared to carry out maintenance activities on all flood control structures every year. Regular monitoring and maintenance are critical to ensure potential problems are identified and addressed quickly to avoid prolonged damage that may exponentially escalate when left unchecked. For example, concrete and/or steel damage needs to be identified and repaired early before it gets worse from prolonged corrosion.

The monitoring and inspection procedures for the constructed project will be written in the OMRR&R Manual and will be provided to the NFS. The intent of the document is to provide the NFS with some clear and comprehensive guidance on the operation and maintenance of coastal storm risk and flood control measures implemented for the project. It will describe how to plan and prepare for high water and storm events and lays out steps to take during emergencies that will help reduce the threat of flooding. The OMRR&R will also explain the types of assistance that USACE can provide to a community before, during, and after a flood. Monitoring and inspections must occur to ensure that the project functions as designed and that the NFS conforms to all OMRR&R recommendations and requirements that will assist in functionality of the project.

Routine maintenance is expected in any project and can be planned for in advance. The NFS will have the primary responsibility for operating and maintaining the project. USACE will provide an OMRR&R manual for each completed construction segment or reach. An example of the type of OMRR&R requirements per feature type is included below. Please note this is not a comprehensive list but instead provides the generalized requirements that will be expanded upon in the OMRR&R Manual to be developed during final design and finalized following project construction.

Periodic Inspection of installed flood control features is a comprehensive inspection conducted by a USACE multidisciplinary team that includes the NFS and is led by a professional engineer. USACE typically conducts this inspection every 5 years on the federally authorized flood control structures in the USACE Safety Program. Periodic inspections include these three key steps:

- Data collection: A review of existing data on operation and maintenance, previous inspections, emergency action plans and flood fighting records.
- Field inspection: Like the visual inspection for a Routine Inspection, but with additional features.
- Final report development: A report including the data collected, field inspection findings, an evaluation of any changes in design criteria from the time the structure was constructed, and additional recommendations as warranted, such as areas that need further evaluation.

Both Routine and Periodic Inspections result in a final inspection rating for operation and maintenance. The rating is based on the floodwall inspection checklist, which includes 125 specific items dealing with the operation and maintenance of floodwalls and associated infrastructure. Each wall segment receives an overall segment inspection rating of Acceptable, Minimally Acceptable, or Unacceptable. If a wall system comprises one or more segments of the project, then the overall project system rating is the lowest of the segment ratings. The NFS must maintain the wall system and associated infrastructure to at least the minimally acceptable standard to remain eligible for federal rehabilitation assistance through the USACE Rehabilitation and Inspection Program (Public Law 84-99).

The NFS should be prepared to carry out maintenance activities on all flood control structures every year. Regular maintenance is critical because many types of problems will escalate exponentially when left unchecked. The NFS should be aware of many ongoing requirements. For example, debris and unwanted growth need to be removed from completed floodwalls, rock armor, and the areas adjacent to floodwalls. Metal gates and other flood gate components need to be painted and greased periodically.

The sheet pile wall condition will be evaluated based off safety and serviceability. Safety is related to the performance of the wall when exposed to beyond-normal service conditions such as unexpectedly poor soil conditions or excessive loading. Serviceability is related to the performance of the wall when exposed to normal service conditions such as excessive misalignment. Two condition indexes are used to evaluate the structure relative to the criteria above. The structural condition index is primarily focused on safety and based on structural analysis of the sheet pile structure. The functional condition index includes both safety and serviceability and is based on field measurements and relies on the subjective opinion of experts.

The concrete cap will need to be inspected for cracking which would require sealing as needed to prevent foreign materials from intruding. The coal-tar-epoxy coating might require additional application in areas where it has come off to maximize corrosion prevention. The rock armor protection as well as offshore bathymetric conditions (e.g., scour) should be monitored and will need to be corrected if stability issues arise. The flood gates should be inspected for damage and ensure the structure maintains proper functionality with floodwall tie in locations.

Beyond these examples of ongoing maintenance, more significant repairs may be necessary from time to time. On occasion, the NFS may need to add or replace stone to control an erosion problem, complete earthwork to repair a land-side protective measure or replace or repair removable flood gates. Segments of sheet pile wall severely damaged from excessive corrosion or from a storm, would require total rehabilitation. Routine maintenance is expected in any project and can be planned for in advanced.

To assist with monitoring, certain tools and instruments are needed and measurements are required. Water surface elevation gauges are recommended to be installed in all areas where storm surge barriers are being constructed. This is to assist in providing accurate real-time readings of the water surface elevations in each area. Other Geotechnical instruments are needed to measure movement of the structures and periodic surveys are required to monitor for possible settlement.

In addition to monitoring and maintenance the NFS will be responsible for deploying/operating the flood gates. The trigger for flood gate deployment will be described in the EAP. The EAP will be completed by USACE, in coordination with the NFS, in PED.

#### 5.1.4.2 Construction Schedule

At the completion of the Puerto Rico Coastal Study and upon approval by the Chief of Engineers of the United States Army, the Recommended Plan would be provided to Congress for authorization and funding. If authorized and funded by Congress, subsequent phases of the project would include PED, construction, and operations and maintenance.

Completion of PED and construction of the Recommended Plan, specifically the pace of construction, is highly dependent on Congressional approval and funding. Assuming an ample funding stream, the Recommended Plan for the San Juan area could be designed and then constructed over a period of 5 to 7 years. Construction sequencing will be dependent on completion of supplemental engineering and environmental studies, however, both floodwalls (Barbosa Park and Marías Skate Park) are recommended to be completed at the same time (under a single contract and mobilization). The construction schedule for the Rincón project area is dependent on many other factors, primarily the large-scale acquisition, and much more difficult to predict. The Rincón project area will likely be a separate contract from the San Juan work.

## 5.2 Rincón Planning Area TSP General Description

The TSP for Rincón includes acquiring the most vulnerable coastal structures and properties along the shoreline in the project area. The intent of the recommended plan is for local and federal governments to establish a program to acquire vulnerable properties along the Rincón shoreline to reduce future economic damages to upland property, structures, and infrastructure. The acquired properties would be reestablished as natural coastline (beach) that would support environmental enhancement, public recreation, and future economic growth and stability. Removing large segments of structures and/or coastal armoring that encroach into the coastal system would also increase shoreline stability by allowing the shoreline/beach to naturally respond to storm events (i.e., the increased erosion due to coastal armoring and the presence of structures projecting into the coastal system adversely affecting cross-shore and long-shore sediment transport would be greatly reduced or eliminated).

As discussed in the Main Report, traditional coastal storm risk management measures such as beach restoration, coastal stabilization structures or armoring, or a combination of these measures were considered for the Rincón area, however, challenges of implementing these measures were quite significant. The primary driving factors include the likely impact to the environment (direct and indirect impacts to upland to offshore habitats and species), the significant historical sand deficit within the project area and adjacent areas, limited sand resources in the local area, and large costs associated with these factors and construction along the eroded beach.

Specifically, the TSP for Rincón includes acquiring approximately 60 to 70 parcels along the Rincón shoreline from R11 to R19 that will ultimately result in a more natural condition of the highly eroded shoreline. The parcels currently targeted to be acquired were selected based on numerous factors, including but not limited to, predicted structure damage(s) from planning models, their physical location in relation to the existing water line, potential impacts to natural coastal processes (at present and into the future), and environmental resources. In general, structures that are not setback from the shoreline have and will continue to experience increased damages and/or condemnation and were shown to have an adverse effect on the coastal system and are recommended to be acquired in the TSP. Figure A-118 below provides a general overview of the proposed parcel acquisition area. Additional details on the Rincón TSP as well as plan formulation details are provided in the Main Report and additional details on the specific parcels to be acquired is provided in the Real Estate Appendix.


**Figure A-118. Rincón TSP General Overview**

### *5.2.1 Additional Engineering Considerations*

The following section provides additional engineering considerations for the Rincón TSP, including design assumptions, constructability and access risks, and uncertainties. These are provided to understand the engineering assumptions and risks of the TSP and to identify additional potential measures that may be necessary to mitigate these risks during future design efforts. Notably, plan formulation risks and uncertainties and the anticipated construction schedule are discussed in the Main Report.

As discussed in the Main Report, the structure and property acquisition process will be developed in detail with the NFS and likely the municipality of Rincón. The process will likely not be accomplished in a short period of time (likely many years) and will be funding driven. The acquisition plan will likely prioritize the most vulnerable structures and/or those causing the largest adverse impact on natural beach processes or the environment. Priority may also be given to parcels abutting one another such that large portions of property may be combined. Once the full suite of structures and acquisition plan is developed, the initial (first phase) properties will be acquired and, if the structures are a primary residence, the residents will be compensated and relocated. Specific details on the acquisition plan are provided in the Main Report.

Once an acquisition plan is finalized and funding secured, the properties will be acquired and the federal and/or local government will solicit a contract for structure demolition. The demolition process will likely involve complete removal of the structure (including the subsurface foundation), utilities and coastal armoring (if present) to provide a natural beach area. Following full site demolition, a small quantity of beach-quality fill may be placed on the site and graded to blend in with the adjacent properties and/or shoreline. Additional improvements such as the planting of native vegetation may also be implemented. Of note, the recommended alternative does not include full beach restoration. A small amount of beach-quality fill will be placed within the structure and/or parcel footprint such that the property will naturally blend with adjacent areas and to avoid an initial eroded condition that may result from structure removal. The fill will only be placed within the footprint of the parcel (or structures) and will not extend any further seaward than the existing structure(s). The fill will be graded to represent a natural beach area to avoid potential environmental impacts and mitigation.

#### 5.2.1.1 Constructability and Access Risks and Uncertainties

The proposed project presents numerous construction challenges. The challenges as well as the approach to reducing the risk associated with these challenges is summarized below.

- Coastal Regulatory Program: The problems in Rincón result from a combination of sediment deficit from the system, continued erosion, and the improper placement and siting of coastal structures and armoring. To limit development of coastal structures and armoring, the NFS should establish and enforce a coastal regulatory program described in Section 4.5.5 and Section 4.7. Without a coastal regulatory program there is no insurance that future structures will be prohibited from the coastal zone. Should structures return to the coastal zone, continued erosion will likely increase and negate the benefits of the proposed plan. Therefore, it is critical that the coastal regulatory program be developed and maintained by the NFS. Additionally, there is residual risk to the remaining structures outside of the TSP in Rincón.
- Construction Access: The preliminary cost estimate developed by the real estate team assumes construction will be land-based and access to the properties will be through the existing roadways. The roadways are relatively small and minor impacts to the roadways and traffic are likely, however, once initial structure demolition and material removal commences, contractors

will likely be able to utilize the landward portion of acquired properties as staging and/or access areas as construction commences throughout the project area. This proposed approach does assume structures will be acquired and demolished in connected sections. This assumption will be further evaluated during acquisition plan development and during PED-level planning.

- Existing Structure Demolition: As mentioned above, the project includes complete removal of the existing structure(s) on the parcel, including the subsurface foundation, utilities, and coastal armoring (if present). Demolition costs will vary based on the size of the structure, location, and other factors. From recent site visits, most of the proposed parcels include coastal armoring consisting of a wide array of various materials including but not limited to rocks, seawalls, and repurposed concrete and steel structures. Structure and debris removal within the coastal zone to provide a clean, sandy beach area will likely be challenging and may require specialized equipment. Increased erosion conditions (resulting in more structure/material in the water) will further complicate demolition activities.
- Utilities: Structure demolition will include severing and capping all existing utilities servicing the seaward structures. Additionally, potential impacts or temporary disruptions to overhead utilities, such as to power and communications, may occur during structure demolition activities. A comprehensive utility survey is not currently available, however, will be performed during PED phase (discussed further below).
- Demolition Material Disposal: The proposed project will include disposing of a substantial amount of waste, including but not limited to concrete foundations and/or walls, timber framing, roofing materials, plumbing and electrical materials, vegetation and other materials. The preliminary plan assumes all construction material can be disposed of in a local or regional area. This assumption, as well as potential beneficial reuse of waste materials, will be further investigated during PED phase.

### *5.2.2 Pre-Construction, Engineering, and Design Phase Considerations*

The following section outlines considerations for PED-level data collection and design work to further address the remaining engineering design risks and uncertainties. While these considerations will be used to detail specific scopes of work to reduce risk during the PED phase, these items also present many areas to further "value engineer" the project to increase cost-effectiveness.

- Utility Surveys: Detailed utility surveys are not currently available. A detailed utility survey will be performed in PED to document underground and overhead utilities, and a utility disconnect and relocation plan will be developed (if necessary). The assessment may also include recommendations for relocating utilities to the landward side of roadways to reduce the risk from potential future storm impacts.
- Structural Surveys: Real Estate provided demolition and relocation costs based on previous and on-going projects in Puerto Rico. A preliminary and/or detailed structural survey was assumed to be performed for the proposed structures to be demolished to refine these costs and identify any additional risks during future construction. This survey will also provide information identify any potentially hazardous materials or those requiring special handling or disposal.
- Hydraulic Modeling: During the PED phase, H&H will perform high fidelity modeling to assess current and future (residual) coastal storm risk. This modeling may be used to further refine the structure and property acquisition plan (identify additional parcels for acquisition) or identify

additional protection measures to reduce residual storm risk to existing property and infrastructure (e.g., roadways and utilities).

- Public Access, Recreation, and Environmental Improvements: The proposed alternative provides additional opportunities for recreation via a wider, sandy beach area in the footprint of current structures, however additional environmental enhancements such as incorporation of a small dune feature and/or planting native vegetation may be implemented to increase the resiliency of the project area. Additional opportunities for increased public access may be in the larger parcel areas, such as increased parking, enhanced sidewalks and connectivity, or other recreation features such as restrooms and picnic benches.
- Significant Changes to the Project Area, Existing Shoreline and/or Design Conditions: The preliminary plan assumes the general project area conditions will be relatively similar to the existing conditions. The plan may require modifications should the general project conditions change. For example, a major storm impacting the area resulting in significantly changed shoreline conditions or structure condemnation, or a major development project in the project area that limits acquisition.
- Alignment and Easements: During the PED Phase, more information and data will be collected, including updated real estate information. Potential real estate requirements for the project area include Fee Acquisitions, Temporary Work Area Easements, and Road Easements. The fee acquisitions and easements are necessary to provide adequate construction access, staging and work areas to complete the project. USACE has assumed access and staging areas will be provided through the existing and future public lands. Additional refinement to the exact acreage and location will be performed in PED. More information on easements and real estate requirements can be found in the Real Estate Appendix.
- OMRR&R: During the PED phase, the monitoring procedures for the project will be written in the OMRR&R Manual for the NFS, who will have the primary responsibility to operate and maintain the project.

# 6 QUALITATIVE RISK ASSESSMENT SUMMARY

Assessing the TSP design failure modes in the feasibility phase of a 50-year federally authorized project minimizes the risk that a plan is under designed going into the PED phase. The USACE, SAJ Risk Cadre completed a qualitative QRA for the Ocean Park TSP, and this assessment is summarized below.

The QRA will look at potential failure modes and consequences from failure. We use this information to judge risk tolerability.

- Are we missing major design features that are needed to address failure modes and need to be included in the cost?
- Is risk As Low as Reasonably Practicable?
- Are we doing enough?
- Should we be doing more or less?
- Is this all the surrounding landscape affording for risk reduction?

Basically, the Risk Cadre allows failure modes and consequences of failure to inform the design rather than just normal design standards (risk-based design vs code-based design). All water impounding structures (levees dams, floodwalls, etc.) are required to include risk informed design as they go through PED and into service; therefore, risk assessment and risk informed design must start in feasibility such that risk informed decisions get captured in the original authority and can be implemented in PED. For specific guidance, Engineering and Construction Bulletin (ECB) 2019-15 (USACE, 2019d), and EC 1165-2-218 (USACE, 2021b) are the best sources.

## 6.1 Background

The USACE, SAJ Risk Cadre along with members of the Project Delivery Team (PDT) have completed a screening level risk assessment for a portion of the Puerto Rico Coastal Study, specifically the Ocean Park Tentatively Selected Plan (TSP) Alt 2 – Floodwall at Barbosa Park & Skate Park, in San Juan and the Rincón Planning Reach. The team completed a qualitative risk assessment to review the proposed project, and to assess if there were potential failure modes not addressed by the current design that could cause large cost increases during PED phase, if there were particularly vulnerable populations that may warrant further risk reduction, verify the project does not violate the Do No Harm concept, and based on review of failure modes and consequences identify revisions to the project that would help the project achieve risk As Low As Reasonably Practicable (ALARP). The qualitative assessment characterizes risk without numerical estimates for life loss or annual probability of failure. As part of this process, the risk assessment team thoroughly examined the background information and site characterization data available for this study area and used this information to complete a Potential Failure Modes Analysis (PFMA) for the project. The PFMA uses the elevation line of protection to review what population would be at risk from failure and where the resulting flood could be life threatening.

The Rincón TSP (Alternative 4) is a portion of the Puerto Rico Coastal Study that involves acquiring approximately 60 to 70 properties along the critically eroded shoreline within the study area. This plan includes no flood protection features that induce incremental risk; therefore, there was no risk assessment performed on this part of the study.

The Ocean Park TSP Alt 2 – Floodwall at Barbosa Park & Skate Park, in San Juan is a portion of the Puerto Rico Coastal Study. The proposed floodwall will mitigate areas of low elevation within the existing line of protection along the coast of San Juan and reduces inundation into the protected area(s) by raising the elevation of the coastal flooding entry points. This TSP will result in smaller and less frequent inundation in San Juan by providing coastal flooding entry points with a floodwall to an elevation of 7 feet PRVD02 reinforced with seaward erosion protection. These modifications to the existing shoreline will be tied into existing flood protection measures or higher ground. The risk assessment team met on January 4 and 5, 2023 to assess the risks posed by the construction of the floodwalls.

The Puerto Rico Coastal Study Ocean Park TSP Alt 2 is in the feasibility stage of design; therefore, the details available at this time are limited to conceptual level designs. Potential Failure modes and risk will further guide the design as it progresses through detailed design and construction. No breach modeling or consequence modeling has been performed for this risk assessment. This assessment does not quantify potential consequences from failure, rather it provides information about the potential population at risk (PAR), as well as where loss of life could occur based on the spatial distribution and types of structures, regional ground surface elevations compared to potential hydraulic loading, storm conditions that would be coincident with a significant hydraulic load, and general level of vulnerability of the population based on these factors.

Low-lying lands make up a large portion of the protected area between the coastline and San Jose Lagoon. This low-lying area is the primary consequence zone for the project. Elevations in this low-lying area range from an elevation of approximately 0 feet to 4 feet PRVD02. Flooding from a breach could create flood depths 5 to 7 feet across this area. The actual depth of flooding would be a function of the storm duration and short duration storms may not come to equilibrium with the surge elevation. Although not a risk associated with the project, direct rainfall may compound potential flood depths.

A top of wall hydraulic loading event would be most likely associated with a tropical cyclone and would occur coincident with on shore, hurricane force winds. The protected area is densely developed with structures ranging from single-story, single-family to multi-story, multi-family structures. Multi-story structures would allow for vertical evacuation; however, residents in single-story structures would have difficulty evacuating and would be forced to move on foot and exposed to the hurricane winds during an attempt to seek higher ground. Almost all structures in this area have bars on the windows to prevent burglary, which could cause entrapment with rapidly rising waters. Incremental life loss is considered probable for a floodwall failure during a top of wall loading event. It is anticipated that a storm of strong enough magnitude to cause a top of wall loading event would be accompanied with evacuations of low-lying coastal areas; however, given the density of population in this area and low economic status of much of the area, 100% evacuation is not probabilistic, and some fraction of the population would be expected to remain and be exposed to the flood.

An object of this qualitative risk assessment is to review the potential incremental consequences area for particularly vulnerable areas to life loss during a flood, where particular focus should be given for further reducing risk. For this project, the low-lying protected area is generally of similar elevation, economic status, and structure type, resulting in similar level of exposure to life threating flood conditions from a breach. Therefore, the protected area is judged to have a relatively consistent potential for incremental life loss from breach and no areas are called out as having significantly higher potential for incremental consequences.

All potential failure modes identified by the team were judged to have been adequately addressed by the design at this phase of the project. The following recommendations were also provided to be addressed during optimization of the TSP or during PED.

### 6.2 Recommendations for TSP

During the risk assessment workshop, the team was able to consider adjustments to the TSP which may further reduce risk, increase benefit(s), reduce uncertainty, or reduce cost. These recommendations are as follows:

- The team recommends the project authority be written to allow changes to the project alignment during PED. When closures are in place, the floodwall will prevent localized drainage from the properties oceanside of the alignment and could cause some economic risk transfer from accumulation of rainfall or wave overwash on these properties. The elevation of existing floodwalls and properties along the proposed alignment should be surveyed and the wall alignment should be optimized to incorporate existing infrastructure into the project where existing infrastructure meets the authorized elevation and provides suitable protection against the flood.
- The property on the west end of the of the Ocean Park alignment is not being acquired as part of the plan and may be seeking permit for development. The team recommends this property be acquired as part of the project to prevent new residential development that would interfere with the floodwall alignment. As an alternative, an easement could be acquired to ensure the wall can be built on the seaward side of the property, or the NFS may be able to impose permitting requirements on the property to build and maintain a seawall not less than an elevation of 7 feet PRVD02.

### 6.3 Recommendations for PED

- The landside of the floodwall at the Skate Park is private property which is intended to be backfilled adjacent to the wall, but not modified to any substantial extent. The Risk Cadre recommends PED include a splashpad or other erosion protection measure on the landside, reducing the risk of overtopping erosion initiating and reducing expected maintenance costs from overwash erosion over the life of the project.
- The team recommends a more detailed survey be performed of the coastline within the Ocean Park project area. This survey should include higher resolution elevation data as well as a visual inspection for drainage features. The information available at this time is a LiDAR scan with 3 by 3-meter resolution, which may inadvertently average elevations between points recorded or entirely miss existing seawalls or other features exceeding elevation 7 feet PRVD0 or conversely miss a low point which can allow for flanking of the floodwall.
- The team recommends PED consider reducing the number of removable flood barriers (closures) to the absolute minimum if not removing all-together. Currently, there are closures on a vacant lot (assuming future development and closures at a structure to be demolished; many if not all of these closures may be able to be eliminated during PED). If closures must be included, incorporate considerations such as protective measures or recessed frames to ensure the risk is as low as reasonably practicable. Additionally, the closures should be of the same general type for ease of installation and adequate storage should be incorporated into the wall structure to prevent theft when barriers are stored.

- An emergency action plan (EAP) will need to be developed to properly coordinate communication and timing for evacuation of population within the area affected by the removable flood barrier closures. Threat matrices will need to be developed that clearly document under what conditions the flood gate closures will be installed and removed, as well as identify who is responsible for the installation and removal. Failure to have a clear EAP communicated to the residence seaward of the closures could cause an increase in life safety risk to the residents in those areas.

# 7 PROJECT ADAPTABILITY AND RESILIENCY

The USACE Climate Change Adaptation Goal is to minimize impacts from climate change and maximize resiliency in the coastal landscape. USACE describes resilience as “the ability to anticipate, prepare for, respond to, and adapt to changing conditions and to withstand and recover rapidly from disruptions with minimal damage.” USACE Civil Works project designs should take into consideration how and if the design can be adapted to account for the effects of sea level change (SLC) and climate change 100 years after the project is constructed. These analyses and recommendations are primarily based on projected SLC and not future economic conditions that may affect project benefits.

## 7.1 Ocean Park

In Ocean Park, the study team has formulated alternatives for coastal flooding coming from the ocean side using the intermediate SLC curve. Some residual risks associated with this approach are the possibility of the SLC trends shifting towards the high SLC scenario and potential flooding from the back-bay under the high SLC scenario. Following a substantial analysis and coordination with the vertical team, USACE chose this formulation strategy due to the uncertainty of the high SLC and the potential exponential increase in inundation exposure from intermediate to high SLC. USACE noted higher inherent risk when formulating a coastal storm risk management (CSRM) plan using the high SLC scenario given the magnitude of the solution needed to buy down that risk (huge exposure area), thus inflating project costs. While a very costly CSRM solution may be justified for the high SLC scenario, that level of cost may not be justified under the intermediate or low SLC scenarios. Therefore, the current approach of formulating a TSP using the intermediate SLC scenario is a good compromise and leaves the PDT with no regrets moving forward. Additionally, assessing damages at the high SLC scenario would necessitate compound flooding quantification and could require more than one study. Further, a much larger exposure/assessment area would have likely resulted (nearly island-wide) if the original study evaluated high SLC scenario vulnerability to areas regardless of economic value or intermediate SLC scenario exposure. If the high SLC were to occur, economic modeling indicates a large increase in damages and engineering modeling indicates an increase in flooding pathways within both the general study area along the coastline and in the adjacent back-bay areas. Back-bay flooding under the intermediate SLC scenario indicates the risk of coastal flooding is low and tolerable within the study area. However, the risk of flooding from the back-bay increases substantially under the high SLC scenario. To account for the possibility of the high SLC scenario, adaptation strategies are considered below. The formulation of alternatives based on the intermediate SLC curve with the inclusion of adaptation strategies, as needed, is an approach where there is a plan for each potential scenario to ensure resilience to the community.

### *7.1.1 Potential Adaptation Strategies for Ocean Park*

In Ocean Park, adaptation will likely encompass a re-evaluation study rather than specific adaptable measures due to an increase in ocean-front and back-bay flooding pathways under the high SLC scenario in combination with the study area’s topography and the extensive shoreline armoring that would be required under the high SLC scenario. The increase in flood pathways extends throughout the entire study area and includes flooding from the coastal and back-bay regions. Specific adaptable measures to the TSP would require elevating the TSP and extending the structures laterally to encompass the entire study area and potentially areas outside of the study area. This re-evaluation study will likely indicate that a full reformulation of solutions is required. Thresholds to determine when adaptation needs to take place will be established and included in the Final Report, based on increases in relative SLC over a specified period of time. It is recommended that should adaptations be considered within 50 years of project construction a post authorization study could be initiated with the USACE or a study could be initiated under Section

216 of the Flood Control Act of 1970 (PL 91-611). If adaptation is considered beyond a 50-year period after construction, the non-federal sponsor could initiate a study (with or without the USACE) to address problems.

During the PED Phase, the monitoring procedure for the project and adaptation strategies will be written in the OMRR&R manual. The OMRR&R manual will discuss the thresholds for adaption, with lead times required for each action. Once constructed, the project will be placed in the USACE's Comprehensive Evaluation of Projects with Respect to Sea-Level Change tool to provide additional forecast for potential adaptation. The purpose of this tool is to inventory and assess the vulnerability of existing USACE projects to the effects of SLC and provide added benefits to other USACE activities.

## 7.2 Rincón

Preliminary modeling indicates there will be residual risk following project implementation primarily due to associated damages from continued beach erosion. First, there is residual risk related to potential future development within the newly restored project area, if not enforced. To mitigate this residual risk and ensure the project benefits are realized, it would be necessary to ensure that development and additional coastal armoring, that may have an adverse effect on the newly restored natural areas, is not allowed in the project area. To reduce this risk the non-federal sponsor should establish and enforce a coastal regulatory program to regulate current and future coastal development. This could be modeled after the Coastal Construction Control Line (CCCL) Program administered by the Florida Department of Environmental Protection (FDEP), which ensures the reasonable use of private property and protects the natural beaches and dunes.

Second, the TSP in Rincón recommends acquiring structures from reach R11 to reach R19, rather than the full extent of R11 to R22. This is due to focusing the plan on the largest extent of structures that experience the most frequent damages. The area south of R19 generally contains large condos with robust armoring in the existing condition and several single-family units that are already condemned.

Third, residual risk remains if erosion continues beyond the acquired properties; the high SLC scenario could further exacerbate erosion damages within the study area. USACE formulated for the intermediate SLC curve and assessed the effectiveness of the TSP under high SLC. If a higher SLC scenario was realized increased erosion associated with higher SLC trends would further affect the structures within Rincón, which could undermine damage reduction benefits achieved under the intermediate SLC scenario. To mitigate this risk, it will be important to monitor erosion rates in conjunction with relative SLC trends over time for potential adaptation within the 100-year adaptation horizon. The formulation of alternatives based on the intermediate SLC curve with the inclusion of adaptation strategies, as needed, is an approach where there is a plan for each potential scenario to ensure resilience to the community.

### *7.2.1 Potential Adaptation Strategies for Rincón*

In Rincón, adaptation could entail additional acquisition of structures, most vulnerable to erosion damages, beyond the TSP based on set thresholds and monitoring. Economic modeling indicates that approximately an additional 10 to 20 structures outside of the current acquisition footprint could be vulnerable to erosion within the 100-year adaptation horizon for the intermediate SLC curve and assuming the background erosion rates continue. Thresholds to determine when adaptation needs to take place will be established and included in the Final Report, based on erosion rates and/or increases in relative SLC over a specified period of time. To monitor the erosion rates within the potential project area the coastal regulatory program, developed by the non-federal sponsor, will provide a methodology to track erosion rates and the shoreline following construction completion through the 100-year adaptation horizon. Additionally, the non-federal sponsor should monitor the shoreline vegetation and replant, as needed, after storm events to further efforts to reduce the severity of erosional effects on the potential project area.

During the PED Phase, the monitoring procedure for the project and adaptation strategies, will be written in the OMRR&R manual. The OMRR&R manual will discuss the thresholds for adaption, with lead times required for each action. Once constructed, the project will be placed in the USACE's Comprehensive Evaluation of Projects with Respect to Sea-Level Change tool to provide additional forecast for potential adaptation. The purpose of this tool is to inventory and assess the vulnerability of existing USACE projects to the effects of SLC and provide added benefits to other USACE activities.

# 8 CONCLUSION

This appendix represents the engineering considerations, modeling, and analyses for the Puerto Rico Coastal Study and is one of eight total appendices that is part of a larger CSRM report. This study used SBEACH, Beach-*fx*, HEC-RAS, and G2CRM to define 50-year CSRM TSPs for the beaches of San Juan and Rincón, Puerto Rico. Existing conditions promote economic and life safety risk to the coastal communities in these locations, which prompted federal action after Hurricane Maria. FWOP damages in Isla Verde and Condado indicate a TSP for both areas is no-action. The TSP defined for the Ocean Park planning reach is focused shoreline armoring, consisting of floodwalls with buried rock armor, at the inundation focal points: Barbosa Park and Marías Skate Park. Historic storm rates and total water level magnitudes in the area guided the TSP in this area to consist of a sheet pile wall designed with rock armor protection and a crest elevation of 7.0 feet PRVD02. The combined results for the Rincón study area indicate no-action is the NED Plan, but analyses of all four P&G planning accounts conclude that the TSP is acquiring the most vulnerable structures and property.

This project considered plans using the intermediate SLC scenario due to the exponential increase in inundation exposure from intermediate SLC to high SLC (higher inherent risk given the magnitude of the solution needed to buy down that risk) and since assessing damages at higher elevations (i.e., the high SLC scenario) would necessitate compound flooding quantification. Identifying specific adaptation actions for all three SLC scenarios at temporal trigger points within the 50-year analysis period will be fully defined between the TSP and the Agency Decision Milestone). Further, a QRA is currently underway and will be included in the final report. Adaptation plans and assessing the risk of TSP design failure should promote adequate design considerations as this project moves into the PED phase of the overall CSRM project.

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