Puerto Rico and Caribbean Beach Network
Planning School
University of Puerto Rico
Rio Piedras Campus

Final Report

Assessment of beach morphology at Puerto Rico Island

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1. Background

An assessment of beach geomorphology is conducted at Puerto Rico coastline from 1977 to 2016 period. This assessment includes both long (1971/77-2010) and short (2015-2016) scale beach geomorphic evaluation for the Island. This project was support by the Coastal Zone Division, Department of Environmental and Natural Resources of Puerto Rico (DRNA) and the National Oceanic and Atmospheric Administration (NOAA), federal number NA14NOS4190142, for the period started on March 2015 to June 2016.

The main project goal is conduct the *assessment of beach morphology at Puerto Rico Island (1970 to 2016)* using the integration of remote sensing, Geographic Information Systems (GIS) and field work techniques. The objectives associated with this goal are: 1) identify coastal types distribution; 2) assess shoreline changes between 1970's and 2010 in Puerto Rico coastline, to identify erosion, accretion and no changes shoreline sites in Puerto Rico; 3) identify beach sites with major erosion problems for this period (20 sites); and 4) study subaerial beach profiles and beach sediment composition (back beach and swash) in selected sites during a year period (2015-2016).

The significance of this study is: 1) develop the first stage of the National Shoreline Changes databank for Puerto Rico (1970's and 2010) ; 2) identify coastal sites with major erosion problems in both large and small scale in the Island; 3) validate research protocols to assess coastal geomorphology using the integration of remote sensing, GIS and field techniques in a Tropical Island System; 4) develop recommendations to the design of coastal management plans and policy; and 5) define a research baseline (databank) to continue shoreline studies for other periods (before 1936, 1936, 1960's, 2016 or 2017). In addition, the information acquired in this study will helps to identify the more vulnerable beach sites with erosion and the possible causes that may produce these changes. This evaluation is very important especially due to beach studies are so complex especially in tropical Islands due to the diverse geological, oceanographical and meteorological variables that acting simultaneous in a small geographic area (Barreto and et. al, 1992). In addition, erosion in coastal areas is very critical when population and economic activities occur near coastlines areas.

2. Study Area

This research includes two main types of coastal assessment at the Island. These are both large and short scales geomorphic analysis. The large-scale study was done in all coastline in Puerto Rico Island for 1970's and 2010 period (Figure 1). The Island is nearly rectangular with an east to west distance of 178 kilometers and north to south of 62 kilometers. The coastal areas of Puerto Rico is divided in five sections based on the general geographic location: northwest (from Manatí to Aguadilla), west (from Aguadilla to Cabo Rojo); south (from Cabo Rojo to Maunabo), east (from Maunabo to Fajardo); and northeast (from Fajardo to Vega Baja). The extension of the coastlines of the main island is 1285.86 kilometers (DRNA).This division was used as a framework for describing coastal geomorphic assessment in this study.   Large-scale study includes evaluation of coastal types, beach inventory and historical shoreline changes. Study of historical shoreline changes were done in 4000 beach sites in the Island. The selection of the sites is based on aerial photo availability and image data quality (georectification, visibility).

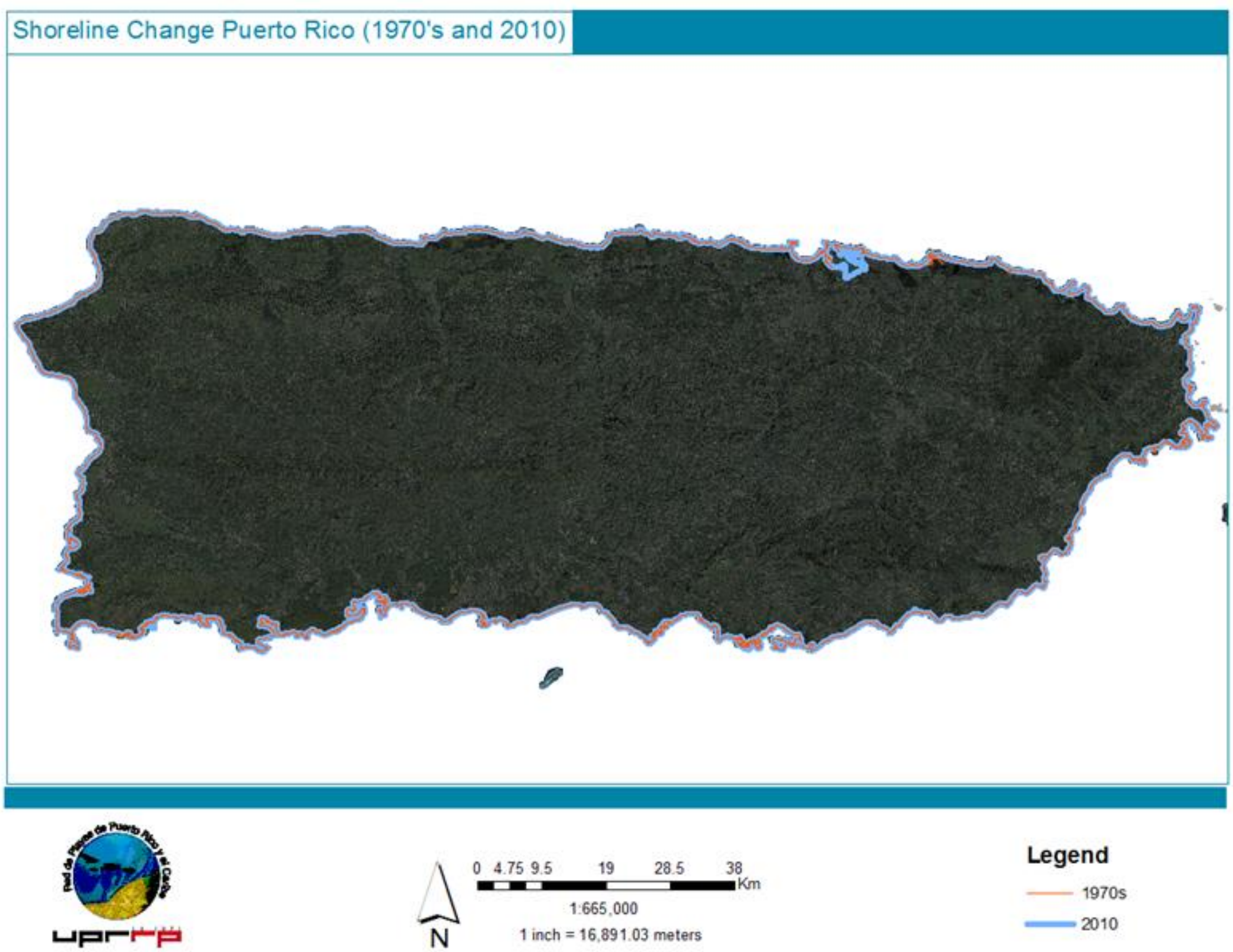


Figure 1. Shoreline changes were assess for beaches in Puerto Rico.

Short-scale analysis includes geomorphic assessment as beach profiling, beach width and sediment characterization in selected coastal sites for 2015-2016 period. This study was conducted in seven beach sites around the Island. Study sites are: Playa Playa Larga at Arecibo (north central), Playa El Mani, Mayaguez (west coast), Playa Santa at Guánica (south coast), Playa Punta Santiago, Humacao (east coast) Fortuna at Luquillo (northeast), Playa Parcelas Suarez at Loíza (northeast) and Playa Puerto Nuevo at Vega Baja (northeast coast) (Figure 2). Some criteria used for the selection of these sites were: 1) historical data accessibility by area; 2) evidence of shoreline changes; 3) geographic location. Permanent beach stations were identified in each beach for data collection.

Figure 2. Study Site (Small Scale assessment). Seven beaches were selected to monitoring beach profiles, beach width and sediment component (backbeach and swash zone).

Playa Grande is located in the north central coast in the municipality of Arecibo, Puerto Rico. Four beach permanent stations were selected for conduct beach profiling, width and sediment collection (Table 1).

Table 1. Permanent beach stations at Playa Grande, Arecibo, P.R.

Playa Grande Arecibo Station 1		
Absolute location	Lat: 18 29' 29.54''	18.49153909
	Long: 66 37' 08.9''	-66.61914232
Playa Grande, Arecibo Station 2		
Absolute location	Lat: -66.61914232	18.49106213
	Long: 66 36' 52.4''	-66.6145698
Playa Grande Arecibo Station 3		
Coordenadas:	Lat: 18 29' 27.05''	18.49084981
	Long: 66 36' 39.1''	-66.61086113
Playa Grande Arecibo Station 4		
Absolute location	Lat: 18 29' 18.1''	18.488382
	Long: 66 36' 08.9''	-66.602498

El Maní beach is located in the west coast in the Mayaguez municipality. Five permanent beach stations were selected to conduct beach monitoring (Table 2).

Table 2. Beach permanent stations at Mani, Mayaguez

Playa El Maní, Mayaguez Station 1		
Absolute location	Lat: 18 13' 55.1"	18.231992
	Long: 67 10' 23.4"	-67.173167
Playa El Maní Mayaguez Station 2		
Absolute location	Lat: 18 13' 51.7"	18.23103981
	Long: 67 10' 23.5''	-67.17320757
Playa El Maní, Mayaguez Station 3		
Absolute location	Lat: 18 13' 48.3"	18.23009278
	Long: 67 18' 23.2''	-67.17313661
Playa El Mani, Mayaguez Station 4		
Absolute location	Lat: 18 13' 43.6	18.22878806
	Long: 67 10' 22.9	-67.17305469
Playa El Maní Station 5		
Absolute location	Lat: 18 13' 42.1	18.22838294
	Long: 67 10' 23.1	-67.17309365

Playa Santa beach is located in the south coast in the Guánica municipality. Four permanent beach stations were selected to conduct beach monitoring (Table 3).

Table 3. Beach permanent stations at Playa Santa, Guánica

Playa Santa, Guánica Station 1		
Absolute location	Lat: 17 56 21.0305	17.93917512
	Long: 66 57 22.2	-66.95616846
Playa Santa, Guánica Station 2		
Absolute location	Lat: 17 56 19.6430	17.93878973
	Long: 66 57 20.4	-66.95568556
Playa Santa, Guánica Station 3		
Coordenadas:	Lat: 17 56 17.3888	17.93816356
	Long: 66 57 18.24.	-66.95506744
Playa Santa, Guánica Station 4		
Absolute location	Lat: 17 56 13.4541	17.93707057
	Long: 66 57 17.4	-66.95483529

Punta Santiago beach is located in the east coast in the Humacao municipality. Four permanent beach stations were selected to conduct beach monitoring (Table 4).

Table 4. Beach permanent stations at Punta Santiago, Humacao

Punta Santiago Station 1		
Absolute location	Lat: 18 09’ 46.7”	18.16302205
	Long: 65 44’ 43.8”	-65.74547138
Punta Santiago Station 2		
Absolute location	Lat: 18 09’ 48.1”	18.16337245
	Long: 65 44’ 38.8”	-65.74392506
Punta Santiago Station 3		
Absolute location	Lat: 18 09' 50.8”	18.16411413
	Long: 65 44' 36.2”	-65.74336697
Punta Santiago Station 4		
Absolute location	Lat: 18 09' 53.4”	18.16484458
	Long: 65 44' 33.5”	-65.74261554

Fortuna Beach beach is located in the northeast coast in the Luquillo municipality. Four permanent beach stations were selected to conduct beach monitoring (Table 5).

Table 5. Beach permanent stations at Fortuna Beach, Luquillo

Fortuna Station 1		
Absolute location	Lat: 18 22' 48.6"	18.38016454
	Long: 65 44' 27.6"	-65.74101121
Fortuna Station 2		
Absolute location	Lat: 18 22' 49.1"	18.38028291
	Long: 65 44' 29.9"	-65.74104345
Fortuna Station 3		
Absolute location	Lat: 18 22' 52.5"	18.38126018
	Long: 65 44' 39.5"	-65.74427245
Fortuna Station 4		
Absolute location	Lat: 18 09' 53.4"	18.16484458
	Long: 65 44' 33.5"	-65.74261554

Playa Parcelas Suárez beach is located in the northeast coast in the Loíza municipality. Six permanent beach stations were selected to conduct beach monitoring in monthly basis (Table 6).

Table 6. Beach permanent stations at Parcelas Suárez, Loíza.

Playa Parcelas Suárez, Loíza Station 1		
Absolute location	Lat: 18 26' 00.3"	18.43342706
	Long: 65 50' 57.1"	-65.85012692
Playa Parcelas Suárez, Loíza Station 2		
Absolute location	Lat: 18 26' 00.4"	
	Long: 65 51' 00.5"	
Playa Parcelas Suárez, Loíza Station 3		
Absolute location	Lat: 18 26' 00.5"	
	Long: 65 51' 03.1"	
Playa Parcelas Suárez, Loíza Station 4		
Absolute location	Lat: 18 09' 53.4"	18.16484458
	Long: 65 44' 33.5"	-65.74261554
Parcelas Suárez Station 5		
Absolute location	Lat: 18 26' 03.0"	
	Long: 65 51' 07.5"	
Parcelas Suárez Station 6		
Absolute location	Lat: 18 26' 04.3"	
	Long: 65 51' 09.6"	

Playa Puerto Nuevo beach is located in the northeast coast in the Vega Baja municipality. Four permanent beach stations were selected to conduct beach monitoring in bimonthly basis (Table 7).

Table 7. Beach permanent stations at Puerto Nuevo, Vega Baja.

Puerto Nuevo, Vega Baja Station 1		
Absolute location	Lat: 18 29' 32.9	18.49249561
	Long: 66 23' 49.4	-66.39705676
Puerto Nuevo, Vega Baja Station 2		
Absolute location	Lat: 18 29' 27.05	18.49084981
	Long: 66 36' 39.1	-66.61086113
Puerto Nuevo, Vega Baja, Station 3		
Absolute location	Lat: 18 29' 31.7	18.49216474
	Long: 66 23' 53.4	-66.39816973
Puerto Nuevo, Vega Station 4		
Absolute location	Lat: 18 29' 27.7	18.4910408
	Long: 66 23' 55.8	-66.39884304

3. Method

A combination of remote sensing, Geographic Information System (GIS) and field studies were used to conduct both large and small-scale geomorphic coastal assessment in this study. Variables as coastal types, shoreline changes, beach orientation, beach profile and beach sediment composition were described both qualitatively and quantitative in this study (Table 8).

Table 8. Geomorphic variables includes in this study.

Variable	Period	Tool
Coastal types	1970's and 2010	Remote sensing and GIS
Shoreline changes	1970'; 2010; 2015-2016	Remote sensing, GIS and field study
Beach Orientation	All period	Remote sensing, GIS and field study
Beach profile	2015-2016	Field study
Beach sediment composition	2015-2016	Field study and laboratory procedures

.

Large-scale beach geomorphic assessment was done using vertical aerial photos dated from 1969,1971,1973,1977 and 2010 (Table 9). Aerial photos from 1971, 1973 and 1977 were used as basemaps for digitizing 1970s shoreline of Puerto Rico (Figure 3). The images were acquired from the Puerto Rico Highways & Transportation Authority (1970's/resolution 2,500 dot per inch) and Planning Board (2010/spatial resolution of 0.3 meters). Not all photos had precise alignment with rectified image of 2010, for instance a rectification process was conducted to allow precise comparisons between photos. Control points as structures followed by roads were used as a control references in the rectification process. On average of three points were used as a control points for conduct rectification. An encountered challenge was to identify points of references in some images because the 1970s image was dominated by vegetation type of land cover and the image did not have structures to match the reference with 2010 image. In addition, problems with photo quality do not allow use all photo data available for this study. Photointerpretation and geospatial analysis (GIS) were used to identify coastal types, shoreline changes and beach inventory.

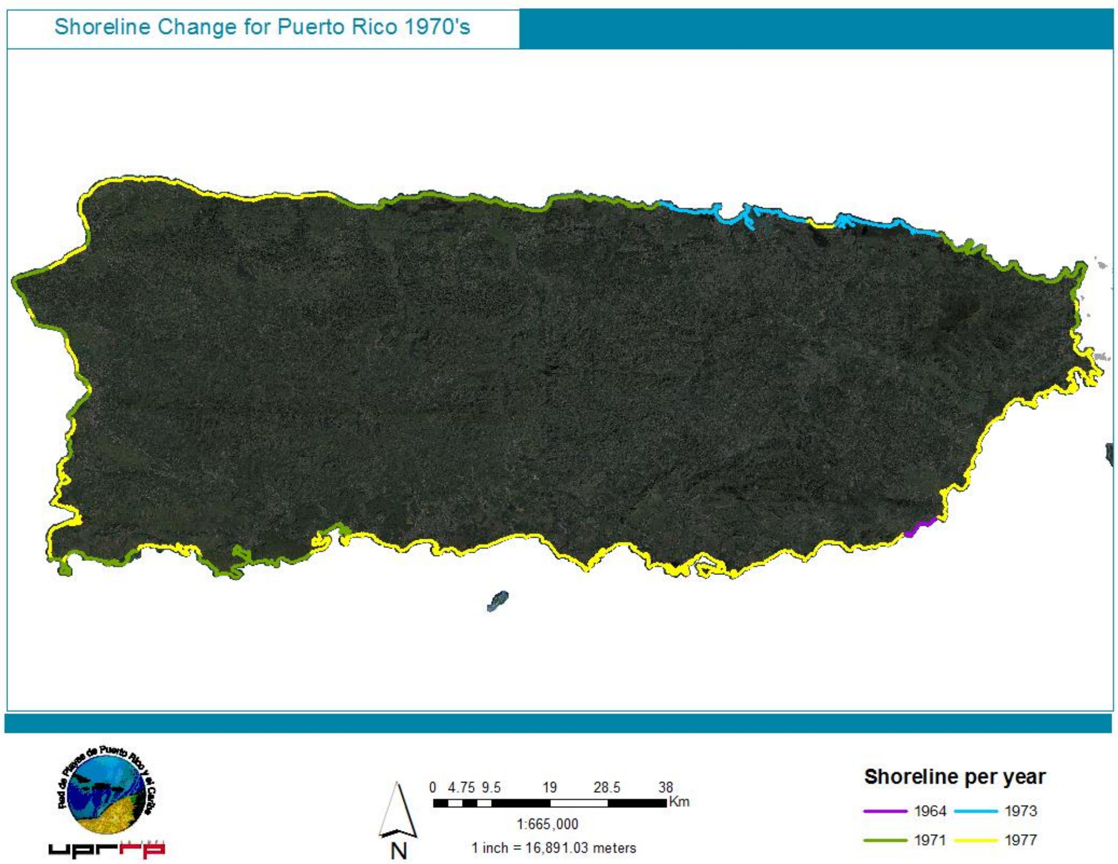


Figure 3. Aerial photos from 1971, 1973 and 1977 were used as basemaps for digitizing 1970s shoreline of Puerto Rico. Vieques and Culebra were not including in 1970's period evaluation.

3.1 Coastal Types

A geodatabase is designed and developed to identify coastal types at the Island. Four main coastal types categories were used in this study. These are beach; rocky coastline; vegetation coastline and alluvial plain. Man-made structures; eolianite; beach rock and non-identify category are additional categories added in the geodatabase to get additional feature description of the coastline. Subcategories as wet/dry and ground water exit lines are included as subcategory of the beach coastal type feature. These subcategories are so important to define the delineation of the shoreline of Puerto Rico for 1970's and 2010. The wet/dry and ground water exit were used as a shoreline standard reference (Boak, E.H. and Turner, I.L., 2005). In this study, coastal type definitions (categories and subcategories) were based on remote sensing and geomorphology point of view (Table 9). A non identify category was used to identify lines that were not well distinguished due to constraint related with spatial resolution, rectification process and cloud cover among others.

GIS ArcMap software version 3.2 was used to delineate all coastal categories and subcategories from the aerial photographs (Six main attributes and eleven domains). A doubt domain has done in the first stage of the study for the lines that need further assessment to ensure the correct interpretation and digitalization.

Table 9. Coastal type categories used in this study.

Category	Sub category	Description (remote sensing and geomorphology)
Beach (sub aerial beach)	Wet dry line Ground water exit	Sediment deposit composed by sand and/or gravel extended from the vegetation line/dune base/infrastructure to the waterline.
Rocky Shoreline	None	A shoreline composed by rock (carbonate/volcanic/metamorphic)
Vegetation	None	Coastal vegetation (mainly wetlands)
Alluvial Plain	None	Coastal deposits composed by mud/lime located near of alluvial fans
Man-made structure	None	Infrastructure as dock, houses, breakwaters.
Eolianite	None	Sedimentary Rock from eolian process
Beachrock	None	Sedimentary rock composed by sand/gravel located mainly in the shoreline
Non-identify category	None	Items that cannot identify during the photointerpretation process due to constraint related with spatial resolution, rectification, cloud cover, among others.

3.2 Beach Inventory

A GIS-based beach inventory was done using vertical aerial photo dated from 2010 acquired from Planning Board Office (Puerto Rico Government). The goal of this inventory was to create a systematic way of accounting for all the beach features of the Island. The beach features identified in this inventory were based on the definition of sub-aerial beach (both remote sensing technique and geomorphic definition): "an accumulation of unconsolidated sediments (mainly sand and gravel) extending from the wet/dry line to a physiographic change inland, such as permanent vegetation, dunes (dune base), base of the rocky promontories or man-made structures. Beaches were delineated using polygons features according to this definition. Polygons were traced from inland limit to wet/dry line. Digitation process started from Cabezas de San Juan (Fajardo) to south Fajardo (counter clockwise) in the main Island (Figure 4). Vieques, Culebra and Caja de Muertos are included in the inventory assessment.   Attributes as beach length, area were calculated using ArcMap software (Figure 4). The design and develop of this inventory was support by the Puerto Rico and Caribbean beach network from University of Puerto Rico, Rio Piedras Campus (Barreto and Valentin, in process of publication).

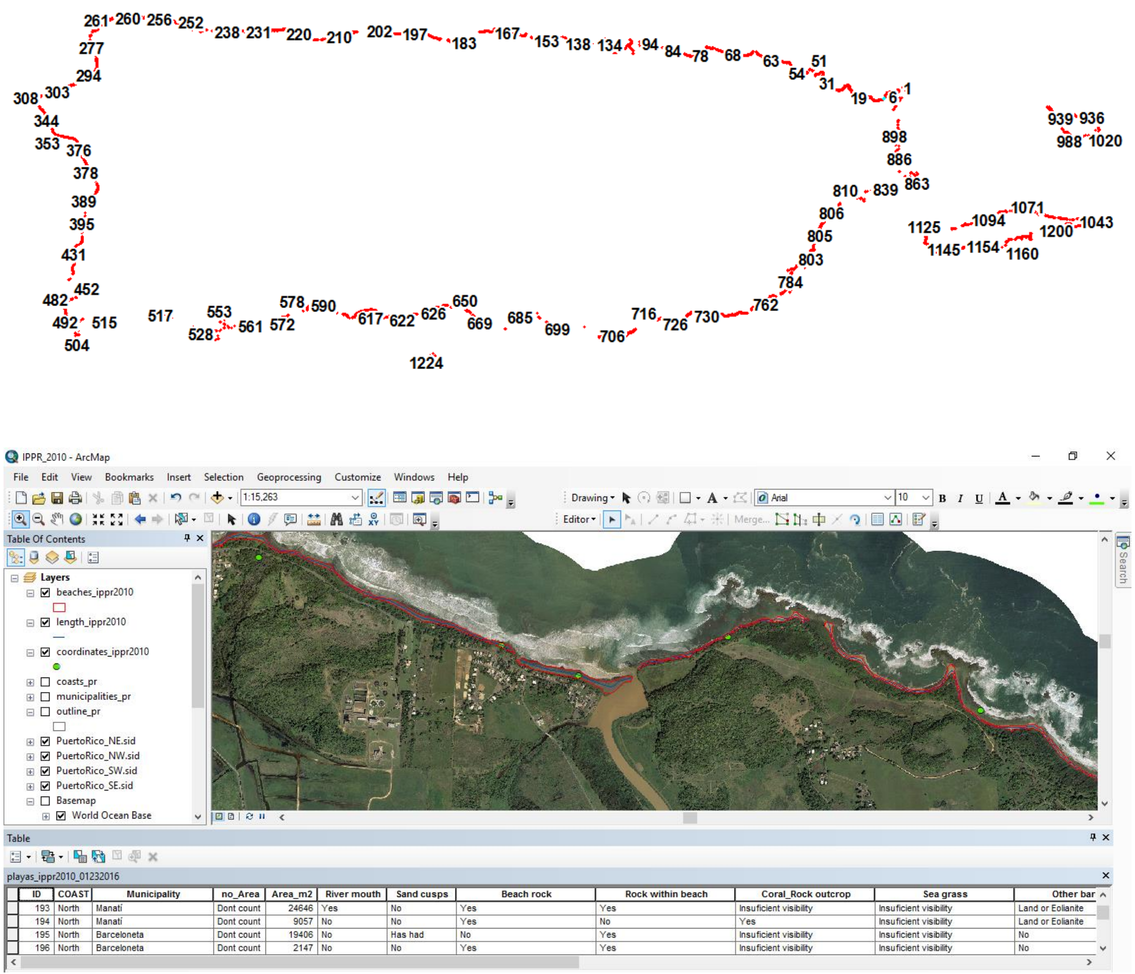


Figure 4. Puerto Rico Beach Inventory (Barreto and Valentin, 2016, in publication process).

3.3 Shoreline Changes

Shoreline position was marked on the photo as the wet/dry line (Boak and Turner, 2005). Use of the wet/dry zone as position indicator as an accurate because the color contrast that marks this zone is sharper than other features in the photo. According to Boak and Turner (2005) this reference is clearly visible in photos. In addition, Hayden and Heywood (1978) infer that this line is a stable marker of the shore. This line is characterized by a change in gray tone (which is caused by the differences of the water content on either side of the run up maxima) between that portion of the wet sand from the most recent high tide and the dry sand. A ground water exit point reference is also used in coastal sites where wet/dry line cannot identified (Figure 5).

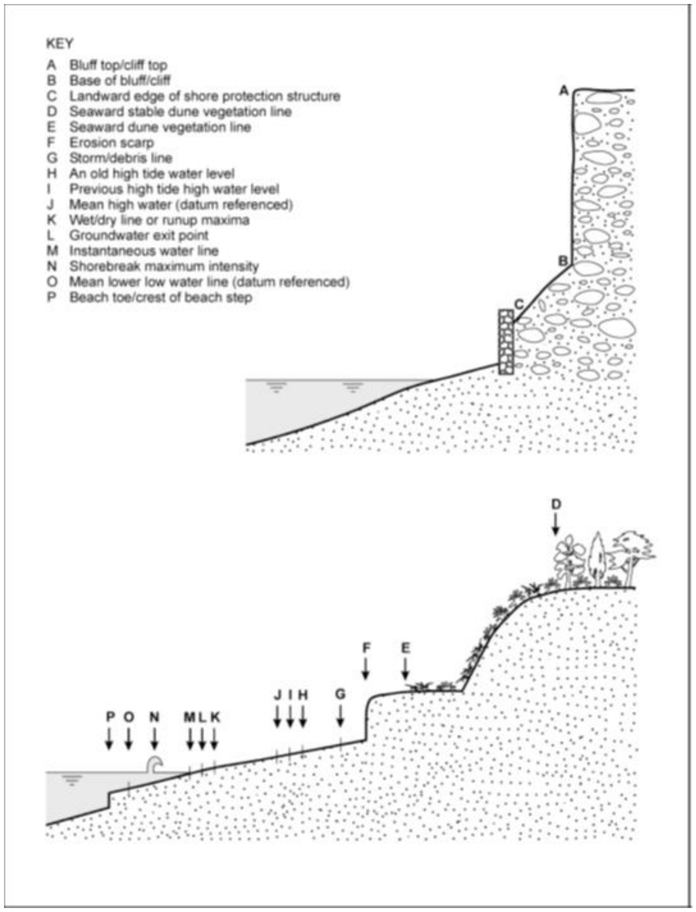


Figure 5. Shoreline indicators. Diagram from Boak, E.H. and Turner, I.L., 2005.

1970s shoreline base line was digitizing using 1971, 1973, 1975 and 1977 photos due to lack of complete coverage of the Puerto Rico coast for the 1977 period. The exact year of the photograph will have used to create each attribute and domain as defined in the shoreline geodatabase data. Shoreline digitalization took place in five separate groups, dividing the territory in five equivalent areas (Northwest, west, south, east and northeast), just as the Aerial Images from the Puerto Rico 2010 Shoreline digitalization from the first phase of the project. Once each group verified, corrected and finished their section, the features are ready for the merge. The five feature classes were opened in an ArcMap document (mxd). There, the areas where the lines connected from one feature class to another were verified and edited in a way that allowed continuity and no overlap. Once the editing process was completed, the merge took place. With the merge tool, the five separate inputs were combined into a single, new feature class containing all features from the shoreline digitalization process for each year (2010, 1970s [general], 1964, 1971, 1973, 1977). 2010, 1970’s, 1964,1971,1973,1977 shoreline of Puerto Rico were created as a final product (feature class/shape file).

3.3.3. Shoreline Changes Overlay 1970's and 2010

An overlay of shoreline features will have done using 2010 and 1970's shoreline feature classes designed in this study. Georeferenced shoreline features helps to identify possible changes in shoreline position for all Puerto Rico coastline. Digital Shoreline Analysis System (DSAS) GIS application was used to calculate detail shoreline changes between 2010 and 1970's shorelines. DSAS is a freely available software designed by the US Geological Survey (USGS) (Thieler et. al., 2009).

For this project, 115 grids were created to measure shoreline changes along the Puerto Rico shoreline using DSAS (Figure 6). Grids were divided as follow: Grid A (from Manatí to Aguadilla); Grid B (from Aguadilla to Cabo Rojo); Grid C (from Cabo Rojo to Maunabo); Grid D (from Maunabo to Fajardo) and Grid E (from Fajardo to Vega Baja). Three thousand eight hundred eight (3,808) beach transects were define to conduct shoreline change analysis in Puerto Rico (Figure 7). Beach transects were located perpendicular from the vegetation line/base of the dune/structure to the shoreline with 20 meters spacing between them and a transect length of 150 meters from the inland baseline. An offshore baseline (mirror baseline) was used in some coastal sites where inland baseline created problems due to the coastal shape. An evaluation of all DSAS transects were done as a final stage of this assessment especially to reevaluate errors that may create DSAS algorithms where is applied to non-lineal shoreline.

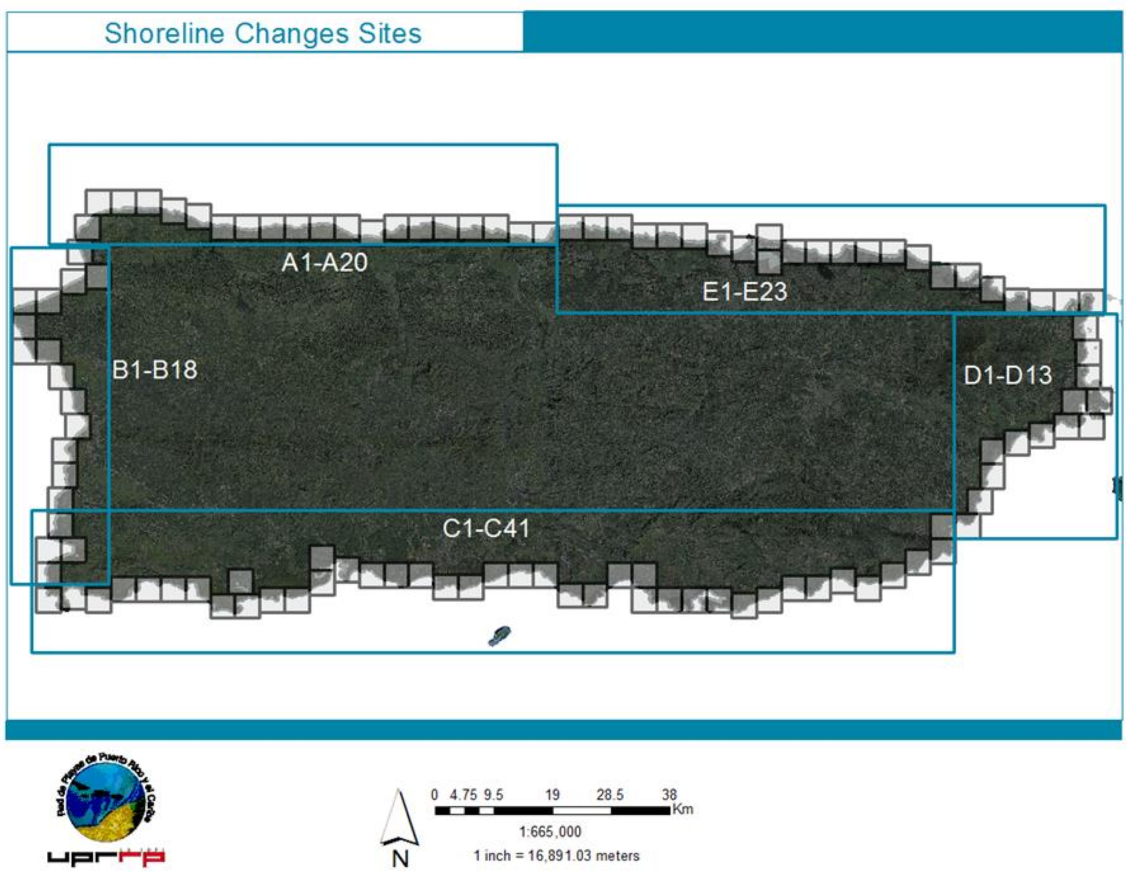


Figure 6. Shoreline grids defined in this study for evaluate shoreline changes at Puerto Rico.

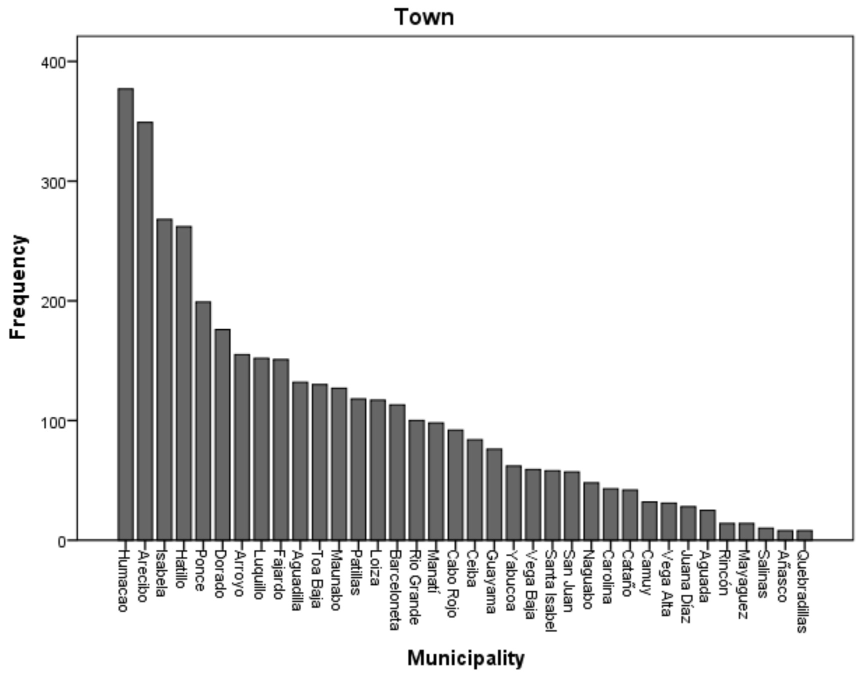


Figure 7. Frequency distribution of beach transects by municipality included in this study.

Shoreline changes length and annual rates were calculated to identify changes in the coastline. Final product will prepare in ArcMap platform in form of maps (erosion and accretion maps), tables and graphs. Shoreline changes classification skin was used to evaluate shoreline changes from 1970 to 2010 (Steward and Pope, 1993). This classification includes severe erosion (≥ -2 meters/yr); very high erosion (-1.21 to -2.0 meters/yr); high erosion (-0.7 to -1.21 meters/yr); moderate erosion (-0.3 to -0.7 meters/yr); low erosion (-0.1 to -0.3 meters/yr), stable (0.1 to -0.1); accretion (≥0.1 meters/yr) (Table 10). A list of severe, high erosion and accretion beach sites of the Island was done as a part of the final evaluation. This information will be valuable for management evaluation and policy.

Table 10. Shoreline Change rates categories (Steward and Pope, 1993)

Shoreline Change Rate	
Accretion	**>.1**
Stable	**0.1 to - 0.1**
Low erosion	**-0.11 to -0.3**
Moderate erosion	**-0.31 to -0.7**
High erosion	**-0.71 to -1.2**
Very high erosion	**-1.21 to -2.0**
Severe erosion	**> -2.0**

3.4 Small Scale Beach geomorphology

Seven beaches were selected for geomorphic assessment in short scale (beach profile, beach width and beach sediments) at the Island. These are: Playa Larga at Arecibo (northwest), Playa EL Mani, Mayaguez (west coast), Playa Santa at Guánica (south coast) Playa Punta Santiago, Humacao (east coast) Playa Fortuna at Luquillo (northeast), Playa Parcelas Suarez at Loíza (northeast), Playa Puerto Nuevo at Vega Baja (northeast) (see figure 1).

Beach profiles and width, beach sediments were collected in bimonthly in all of the selected beaches except Parcelas Suárez, where monthly beach profiles were performed due to the severity of erosion problems. We started collect field data on June 2015 after a detail evaluation of the study sites and local conversation with communities' members. Additional beach monitoring was done during the occurrence of tropical storm events in the areas. The data were mainly collected on June (2015), August (2015), September (2015), October (2015), December (2015), February (2016), June (2016). The data collected in the first weeks of September correspond to the effects of tropical storm Erika, which passed thru the southern coast of Puerto Rico. Data collection was also done during the passage of hurricane Joaquin on the North Atlantic Area during October 2015.

3.4.1. Beach profiling and beach width

The beach profiles were collected using a submetric Global Positioning System (GPS Trimble GeoXplorer 5) through mapping procedure (Figure 7). ESRI ArcPad and ArcMap softwares were used to design a geodatabank (Barreto and Cabrera, in publication process), data acquisition and evaluation. The databank includes fields as latitude, longitude, elevation and comments. North American Datum 1983 (NAD 83) was used as a horizontal datum in this study. The GeoXplorer 5 is calibrated using the new absolute vertical Geographic Datum for each beach selected in this study for increase vertical measurement precision. Vertical Reference used in this study was Geoid 12A PRVD02-PR vertical datum 2002. An additional vertical calibration was performed in each site base on geographic location (Table 11).

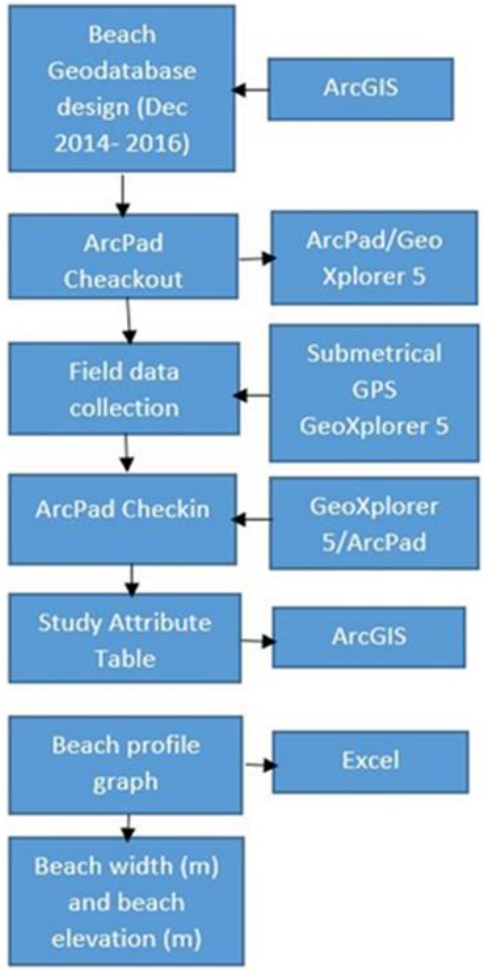


Figure 7. Conceptual Map of Beach profiling method through mapping using submetrical GPS (Prepared by Nahir Cabrera, Barreto and Cabrera, in publication process).

Table 11. Vertical correction coefficient by study site.

Beach	Vertical calibration
Playa Grande, Arecibo	
Vertical Correction	-44.45
El Maní, Mayaguez	
Vertical Correction	-41.815
Playa Santa, Guánica	
Vertical Correction	-40.25
Punta Santiago, Humacao	
Vertical Correction	-40.52
Playa Fortuna, Luquillo	
Vertical Correction	-40.52
Parcelas Suárez, Loíza	
Vertical Correction	-42.490)
Playa Puerto Nuevo, Vega Baja	
Vertical Correction	

Minimum of four beach permanent stations were selected to run beach profile. Beach profile lines started from a permanent location to the wet line for each beach. A polyline was used for run the beach profile from the backbeach to the swash zone. The process is repeated in all permanent stations. The unit provides also a predetermined attribute table (mapping geodatabase) for collect other environmental data, such as beach orientation, beach sediment composition, beach morphology features, wave period and height and other qualitative data (Barreto and Cabrera, in publication process). ArcPad software is used to transfer the data from the GeoXplorer equipment to the ArcGIS project. Once the data is transferred is evaluated using ArcGIS ArcMap project and EXCEL was used to graphic beach profiles based in absolute geographic coordinates.
We done approximately 232 beach profile lines using the GeoXplorer from June 2015 to August 2016.

3.4.3. Beach Sediments
Beach profile sediments were collected for each beach profile station in bimonthly basis. Five hundred seventeen (517) beach sediment samples were collected in the backbeach and swash zone. In order to measure the biogenic/terrigenous content, a gram of dry and clean sediment was weighted. Placed in a pretty dish and then a hydrochloric acid (10% of preparation) was added to dissolved the carbonate. The residual sediment then was washed with distilled water, dried in the oven, and weighed to determine the terrigenous component of the sample.   Sediment

composition test was done at the new laboratory of Beach Process and Sedimentology located at the University of Puerto Rico, Rio Piedras Campus.

4. Assessment of beach morphology at Puerto Rico Island

Beach changes have identified in Puerto Rico during the last decades, with erosion causing major problems in many sites. Beach changes are so complex especially in tropical Island due to diverse geological, oceanographical and climatological variables that acting simultaneous in a small geographic areas (Barreto et. Al, 1992). Variables as waves regime, tropical storms (Caron, V., 2012; Morelock, J. and Barreto, M., 2000; Nebef, S.H. et.al., 2013; Kish, S.A, and Donoghue, J.A., 2013), swells (Ba, A. and Senechal, N., 2013), sea level (Schwartz, M., 2005), Human activities, such as Land Cover and Land Use Changes (LCLUC) (REF), dams (REF) and coastal infrastructure build-up (, M. at al., 2014; Delgadillo-Calzadilla, et. al., 2014; Martins, K.; Pereira, P.S.; 2014), sand extraction (Barreto, 1997) may affect the supply of sand to the beaches. In addition, erosion in coastal areas is very critical when population and economic activities occur near coastlines areas. The following section includes a detail description of the scenario of coastal/beach condition at Puerto Rico.

4.1 Coastal types

Four coastal main types were identified in Puerto Rico. These are beach, rocky, mangroves and alluvial plains coastlines (Figure 8). Beach is the more occurring coastal type at the Island (30%) followed by vegetation coastal type. Mangroves mainly compose the vegetation coastal type. Rocky shoreline is the third more occurring coastal type identified in this study. Rocky coastline includes volcanic, sedimentary and metamorphic rocky coastal types. Alluvial coastal plain is the coastal type less appeared in the Island. This coastal type is mainly found in the south east of the Island.

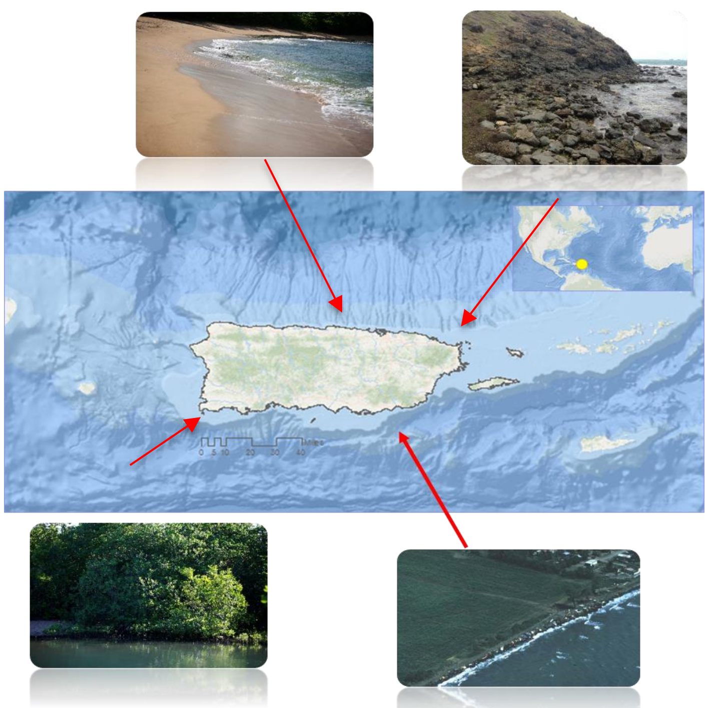


Figure 8. Coastal types in Puerto Rico

Man-made coastal type was also identified in the coastline of the Island. This category includes all non-natural structures built-up in the shoreline. Structures such as houses, buildings, breakwaters, docks, marinas, among others were included in this category. This category is so important because sometimes these structures reduce the natural protection of the coast and promote erosion. Many coastal modifications occurred during the transition from the agriculture to industrial economy from 1950 to 1970. The arrival of new industries, refineries and heavy production factories required the construction of port facilities, different types of breakwater and concrete structure along the coast (Barreto, 1997).

Evaluation between coastal types between 1970's and 2010 photos were execute to identify coastal types for both period (Figure 9). However, quantitative evaluation of coastal types cannot conduct due to coastal features cannot identified in all photos due to spatial resolution and quality (no-identify category). In addition, 2010 coastal types evaluation includes Vieques and Culebra Islands. Therefore, qualitatively evaluation indicated that man-made structures might increase along the shoreline for 2010 period at the Island.

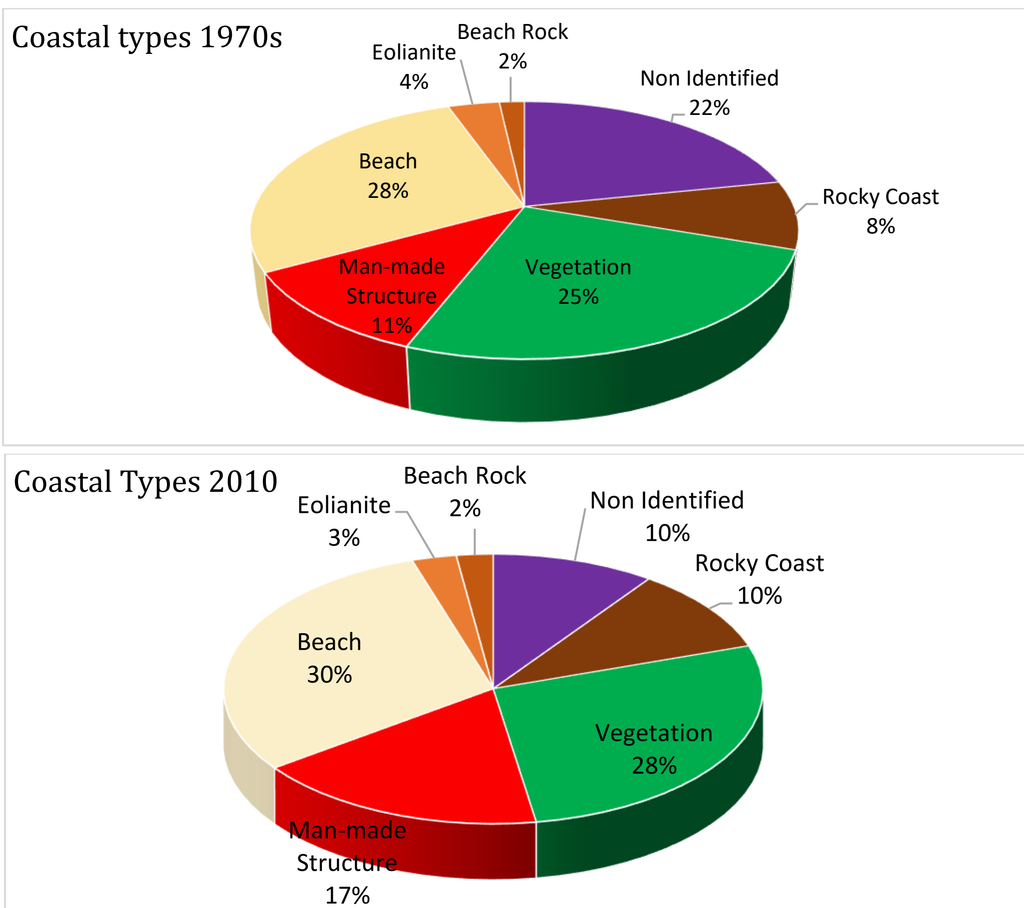


Figure 9. Coastal type distribution at Puerto Rico (1970 and 2010)

4.2 Beaches

The Island of Puerto Rico has 1225 unit of beaches for 2010 period. Beach units are identified for the main Island of Puerto Rico, Vieques, Culebra and Isla de Caja de Muertos (Figure 10). The municipalities with major amount of beach units are: Vieques (172), Cabo Rojo (127), Culebra (111), Ceiba (60) and Rincón (53) (Figure 11). These beaches are mainly short and narrower beaches, with a lunate shape located between rocky shorelines.

Figure 10. Puerto Rico beach inventory (2010) (Barreto and Valentín). a. Map showed all beach units identified in the inventory. b. An example of a beach unit (beach polygon), Playa Sucia, cabo Rojo.

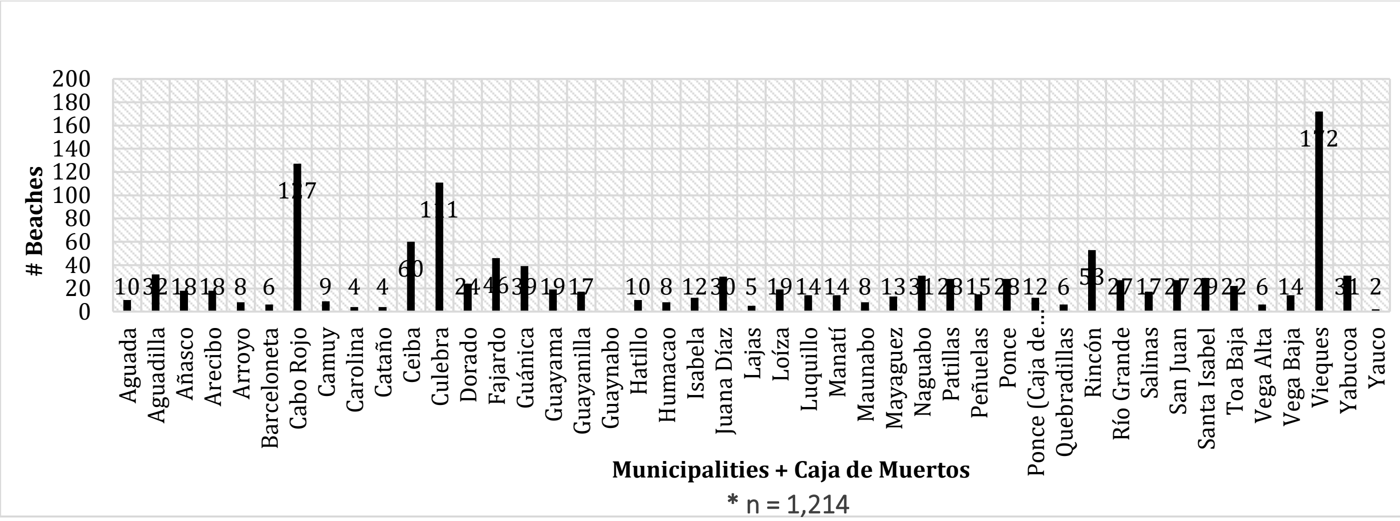


Figure 11. Beach unit distribution by municipality (2010). A beach unit is defined by the presence of geomorphic indicator as rock, structures that can delineate the lateral sediment deposits.

The subaerial beaches with major sandy areas are located at Loíza, Vieques, Isabela and Arecibo (Figure 12). Many of these sites are located near of submarine sand deposits as Escollo Arena (Vieques) and Isabela. The longest beaches are located in Loíza (Piñones Beach), Isabela-Aguadilla, Dorado (Mameyal Beach).

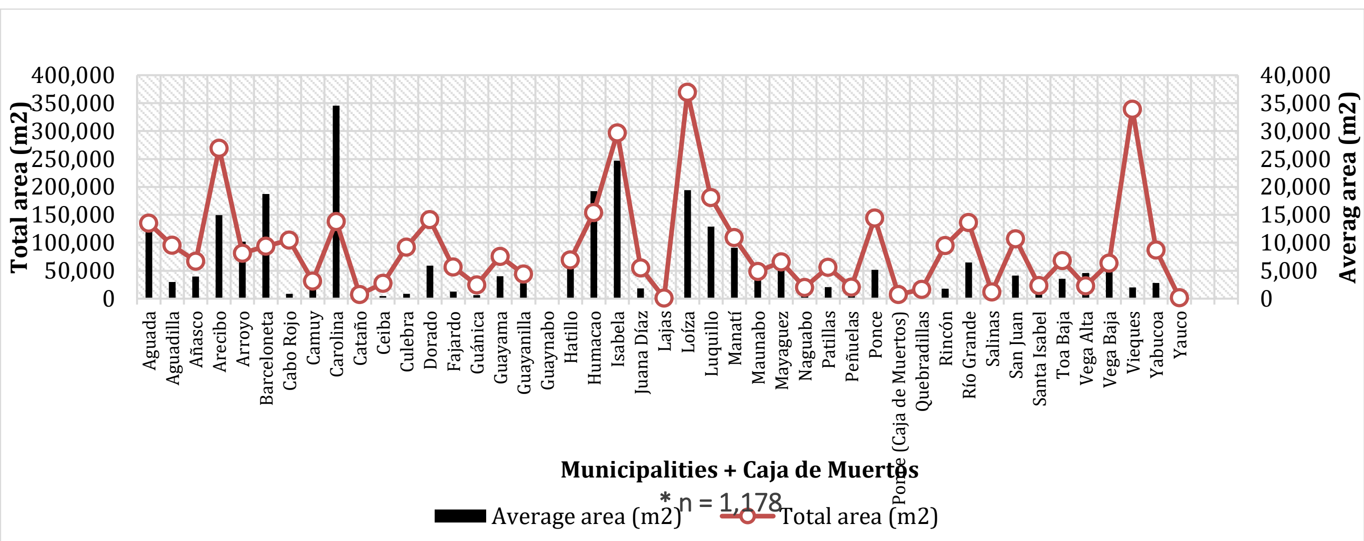


Figure 12. Total (m^2) and average area (m2) and average area of beaches by municipality (2010)

The 15 municipalities that showed major beach length are: Añasco, Loíza, Rincón, Carolina, Aguada, Luquillo, Arroyo, Humacao, Barceloneta, Hatillo, Dorado, Isabela, Juana Díaz, Manatí and Río Grande (Figure 13 and Table 12). The 10 municipalities with minor percent of beaches in their coastal sites are: Guaynabo (none), Lajas, Salinas, Santa Isabel, Cataño, Ceiba, Naguabo, Peñuelas, Guánica and Guayanilla. This information is important to evaluate the distribution of governmental funds to maintain beaches and define coastal vulnerability. Beaches as a soft coastal type barrier may more vulnerable to the swells compare to rocky shorelines.

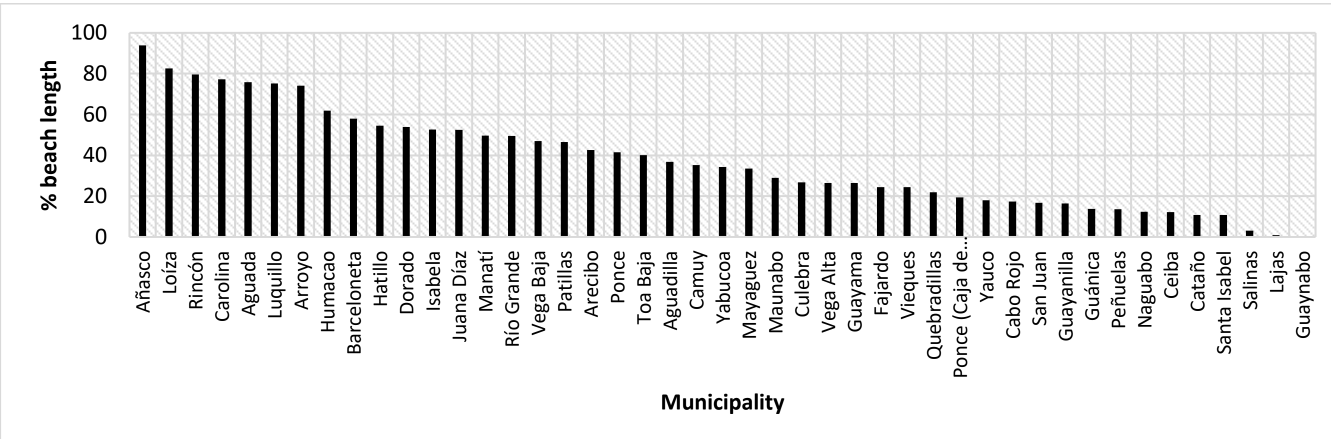


Figure 13. Distribution of beach length (%) by municipality, 2010 (from mayor to minor length)

Table 12. Beach shoreline length (percentage) by municipality (from major to minor length)

Municipality	coastal length (km) - Municipality	beach length (km)	% beach length (Km) by municipality
Añasco	6.13	5.75	94
Loíza	21.27	17.58	83
Rincón	13.26	10.55	80
Carolina	5.86	4.52	77
Aguada	11.47	8.69	76
Luquillo	11.90	8.95	75
Arroyo	8.52	6.32	74
Humacao	20.85	12.89	62
Barceloneta	8.99	5.21	58
Hatillo	8.62	4.70	55
Dorado	16.36	8.83	54
Isabela	18.87	9.94	53
Juana Díaz	14.49	7.59	52
Manatí	14.68	7.29	50
Río Grande	17.91	8.85	49
Vega Baja	12.59	5.91	47
Patillas	16.53	7.69	47
Arecibo	24.94	10.62	43
Ponce	30.91	12.84	42
Toa Baja	16.20	6.48	40
Aguadilla	16.61	6.11	37
Camuy	7.52	2.65	35
Yabucoa	20.20	6.93	34
Mayaguez	20.14	6.73	33
Maunabo	12.31	3.56	29
Culebra	44.66	11.93	27
Vega Alta	5.70	1.50	26
Guayama	37.34	9.85	26
Fajardo	32.76	8.01	24
Vieques	135.63	33.18	24
Quebradillas	6.33	1.38	22
Ponce (Caja de Muertos)	7.52	1.46	19
Yauco	0.93	0.17	18
Cabo Rojo	77.70	13.43	17
San Juan	34.35	5.73	17
Guayanilla	27.33	4.49	16
Guánica	32.98	4.53	14
Peñuelas	22.81	3.12	14
Naguabo	21.22	2.63	12
Ceiba	53.25	6.47	12
Cataño	9.80	1.06	11
Santa Isabel	27.36	2.95	11
Salinas	46.23	1.44	3
Lajas	34.73	0.33	1
Guaynabo	2.18	0.00	0

4.2.1 Beach Orientation

Beaches showed different shapes and orientation at the Island. Major beaches includes in this study showed north and northwest orientation (Figure 14). These beaches are located in the north, northwest, west and northeast of the Island presenting irregular shapes as lunate, concave form. This finding is very important to understand the possible impact of swells approaching from the north and northwest associated with cold front systems. Flamenco beach is an example of a beach unit with different beach orientations (Figure 15).

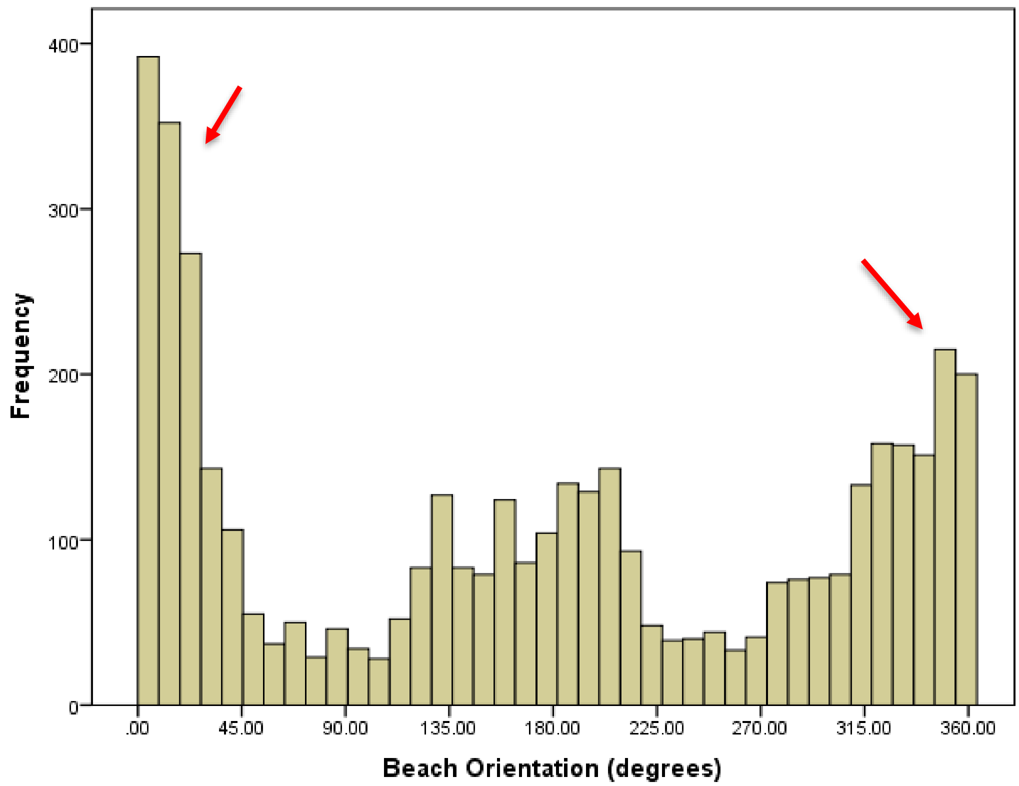


Figure 14. Beach orientation frequency distribution at Puerto Rico, 2010.

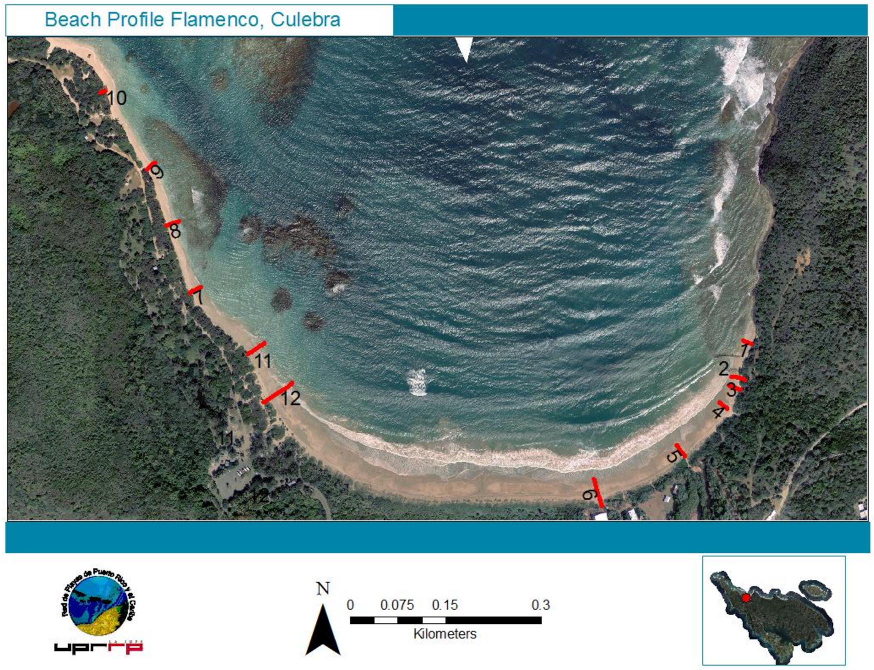


Figure 15. Beach Stations at Flamenco Beach, Culebra, 2010. The coastal site showed different beach orientations. These are: west and northwest (stations 1 to 5), north (station 6), northeast (stations 7 to 12).

4.2.1 Shoreline Changes from 1970's to 2010

An overview of shoreline changes showed a variety of erosion and accretion along the Puerto Rico coastline position from 1970's to 2010. Loss of sand is the major event found in the majority of beaches from 1970's to 2010. Approximately, 60% of the beaches included in this study suffered erosion in Puerto Rico for this period. Accretion is identified in 40% of the beaches in the Island (Figure 16).

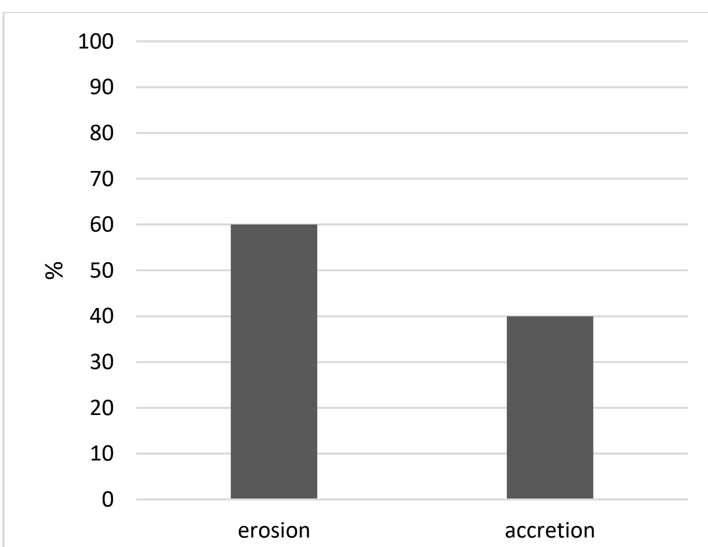


Figure 16. Distribution of accretion and erosion (%) in beaches at PR (1970's and 2010).

Seven main categories (based on a US Army Corps of Engineers model) were used to describe in detail shoreline change rates in this study (Steward and Pope, 1993) as explained in session 3.3. These are: severe erosion, very high erosion, high erosion, moderate erosion, low erosion, stable and accretion (table 10).

Approximately, twenty one (21) percent of beaches show shoreline stability for this period. Low (15.8%) and moderate (14.9%) erosion rates are the type of erosion category more occurring in beaches at the Island for this period. High (3.1%)) and very high (5%) erosion rates were identified in this study (Figure 17). No severe erosion sites were identified from 1970 to 2010 period.

	Frequency	%	%	Cumulative %
Accretion	1533	40.2	40.2	40.2
High Erosion	119	3.1	3.1	43.3
Low erosion	601	15.8	15.8	59.1
Moderate erosion	570	14.9	14.9	74.0
Stable	802	21.0	21.0	95.0
Very High	190	5.0	5.0	100.0
Total	3815	100.0	100.0	

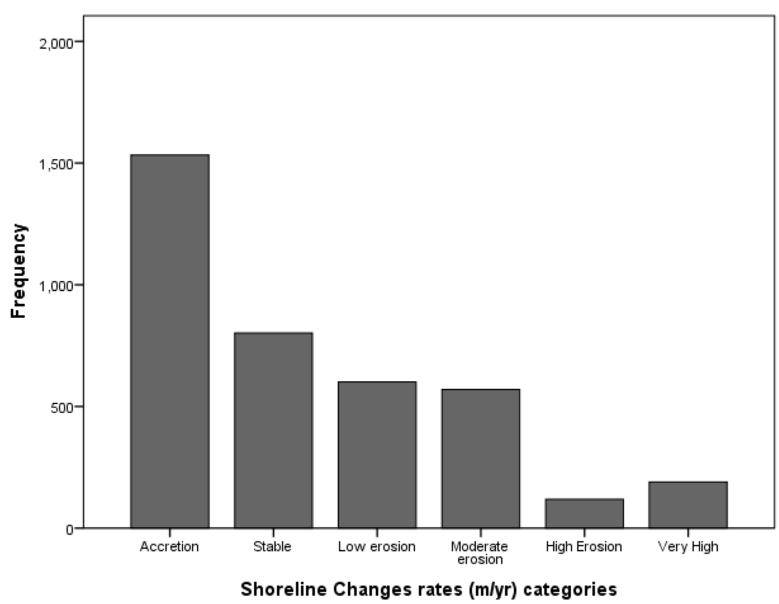
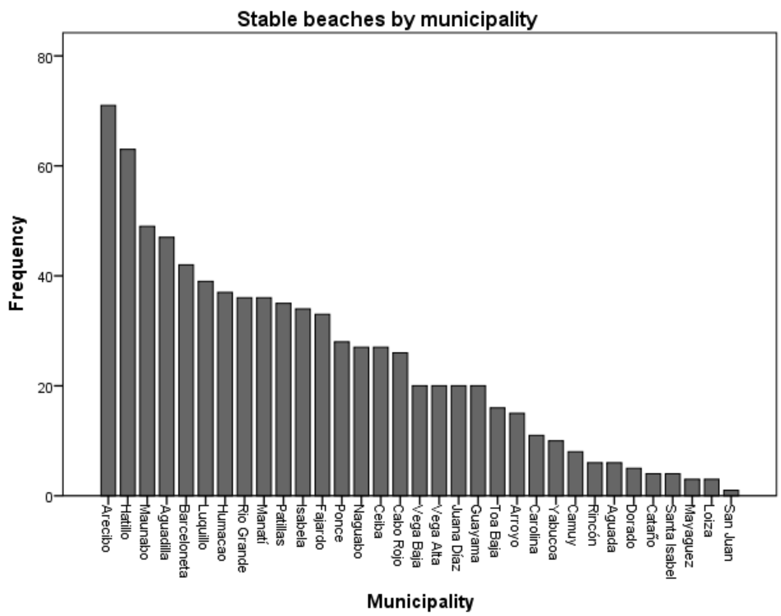


Figure 17. Frequency distribution of shoreline changes rate categories.

Stables beaches are found at Arecibo, Hatillo, Maunabo, Aguadilla, Barceloneta, sectors of Luquillo, Humacao and Rio Grande. More stables beach sites are located at Patillas, Barceloneta, Ceiba, Maunano from 1970's to 2010. Accretional beach transects were identified at Humacao, Arecibo, Ponce, Arroyo and Isabela (Figure 18).



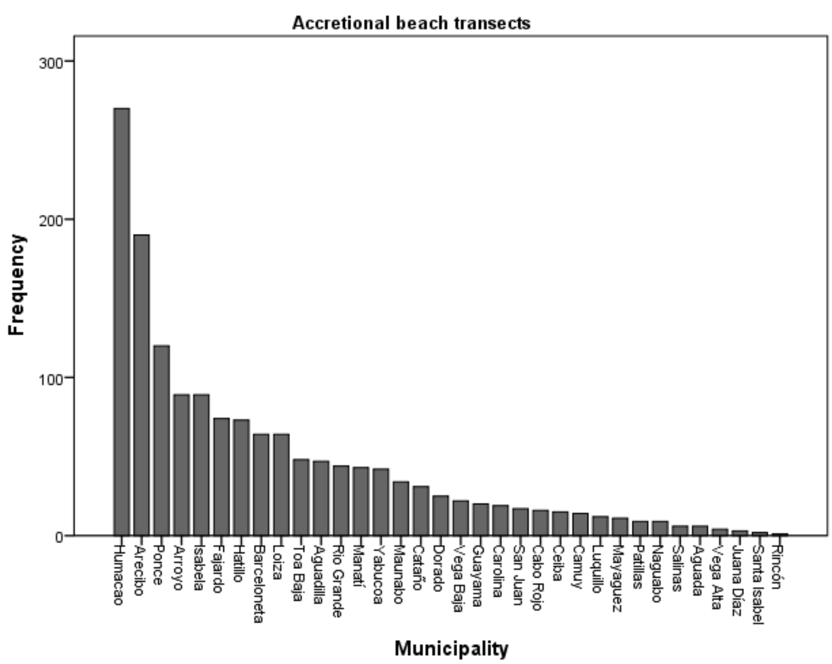


Figure 18. Frequency distribution of stable and accretional beach transects by municipality, 1977-2010

Major accretion rates were identified in beach transects at Arroyo (2.30 m/yr), Salinas (3.8 m/yr), Ponce (1.76 m/yr), Camuy (1.62 m/yr), Yabucoa (1.65 m/yr), Hatillo (1.29 m/yr) and Arecibo (1.24 m/yr). Major loss of sand was identified at Dorado (-1.94 m/yr), Loíza (-1.93 m/yr), Arroyo (-1.28 m/yr), Toa Baja (-1.40 m/yr), San Juan (-1.21 m/yr) (Table 13, Figure 19 and 20). An interesting accretion event was measured at Salinas where a coastal lagoon appeared in the new accretion scenario at Salinas. See detail erosion/accretion maps (115 maps) in the Atlas of Puerto Rico shoreline changes prepared as a part of this report.

Table 13. Major accretion and erosion rates in beach transects included in this study (1970 to 2010)

Accretion		
Transect	**CHANGE RATE**	**Municipality**
418	**1.24**	Arecibo
840	**1.29**	Hatillo
989	**1.62**	Camuy
1506	**1.58**	Mayaguez
1767	**1.76**	Ponce
1996	**3.80**	**Salinas**
2137	**2.30**	Arroyo
2551	**1.65**	Yabucoa
3165	**1.29**	Fajardo
3703	**1.20**	Loiza
3892	**1.32**	Toa Baja

Erosion		
Transect	**CHANGE RATE**	**Municipality**
339	**-1.04**	Arecibo
1153	**-1.04**	Isabela
2201	**-1.28**	Arroyo
2626	**-1.27**	Humacao
3618	**-1.93**	Loiza
3786	**-1.21**	San Juan
3971	**-1.40**	Toa Baja
4162	**-1.94**	Dorado

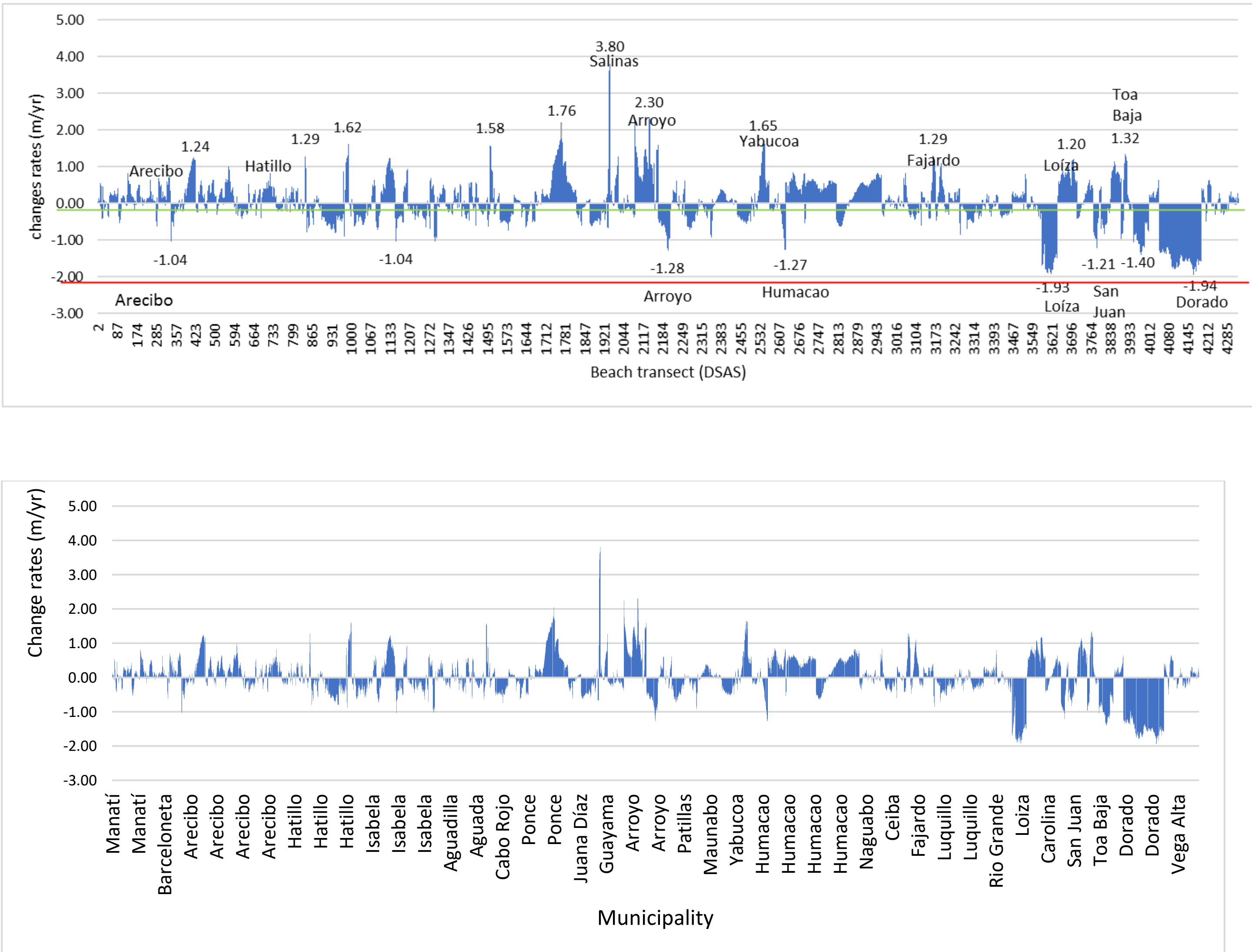
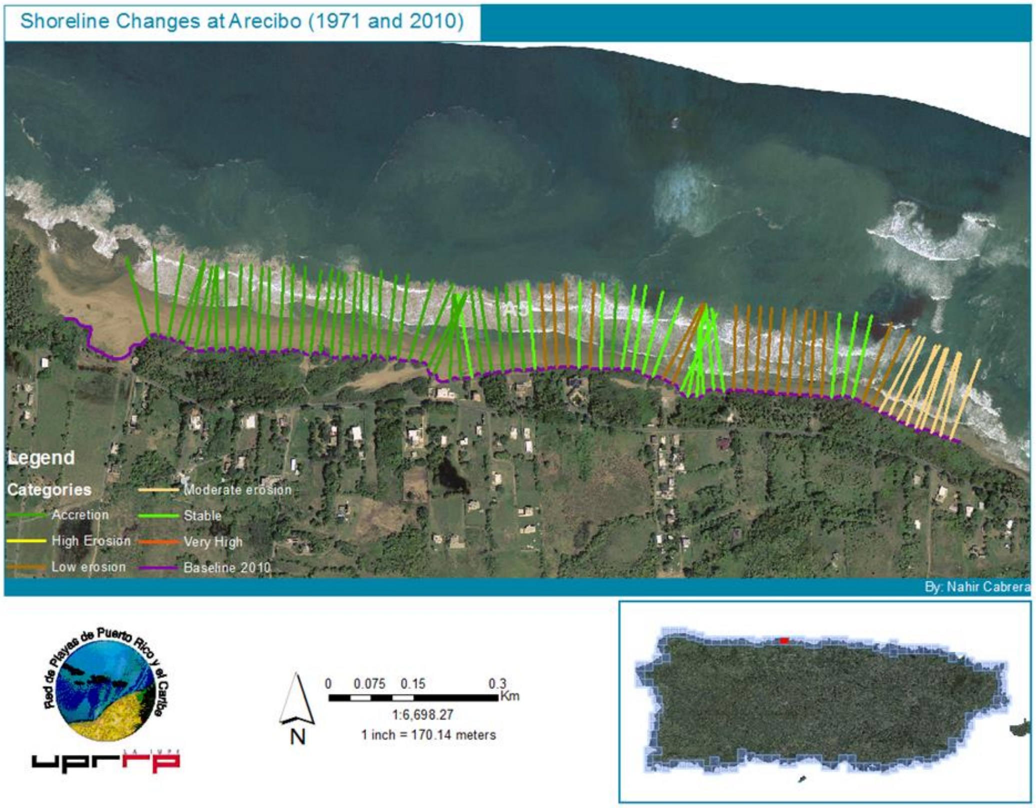


Figure 19. Shoreline Change rates (m/yr) at Puerto Rico, 1970's and 2010.



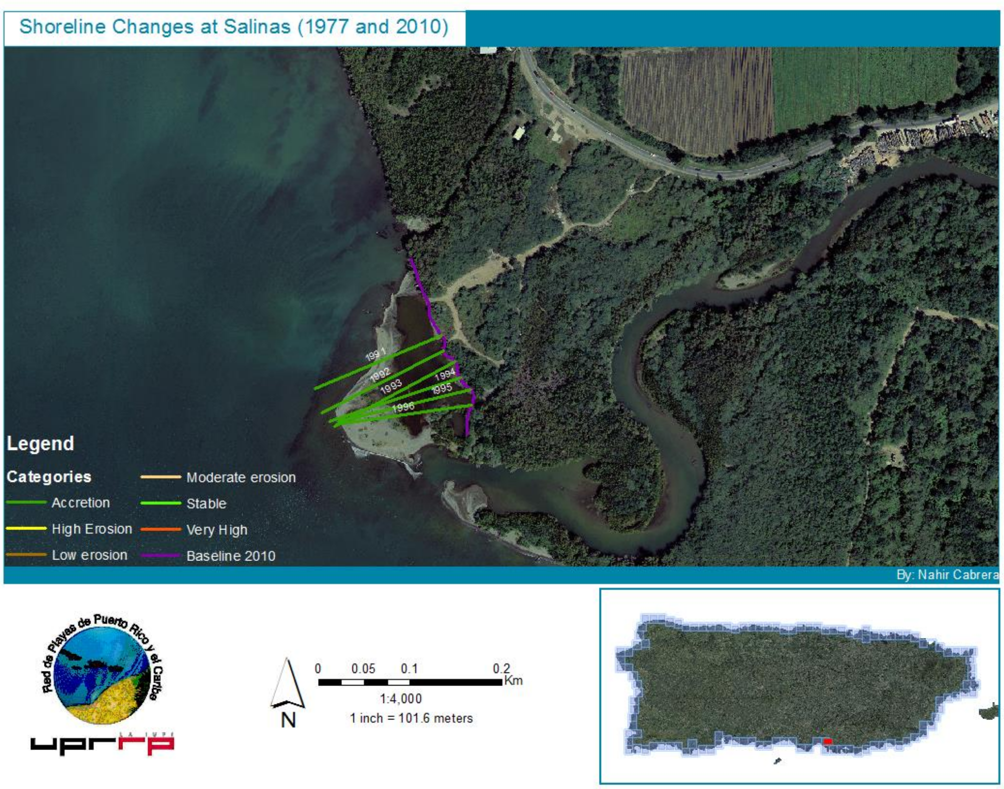


Figure 20. Accretion beach at Arecibo and Salinas, Puerto Rico (1970's to 2010)

4.3 Beach Width

One hundred four (104) beach widths measurement were collected from June 2015 to August 2016 in all selected beaches. Beach width ranges from 0.1 to 128.7 meters. Major beach widths were identified at Playa Grande at Arecibo where beach widths ranges from 20 to 128.71 meters. The wider beach plain is located in station 1 at Playa Grande. Smaller beach widths were measured at Fortuna Beach, Luquillo. Severe loss of beach extension was identified in the western site where is located the residential and touristic areas. Differences in beach widths can identified by stations per beach. This can be related with with beach orientation of each segment.

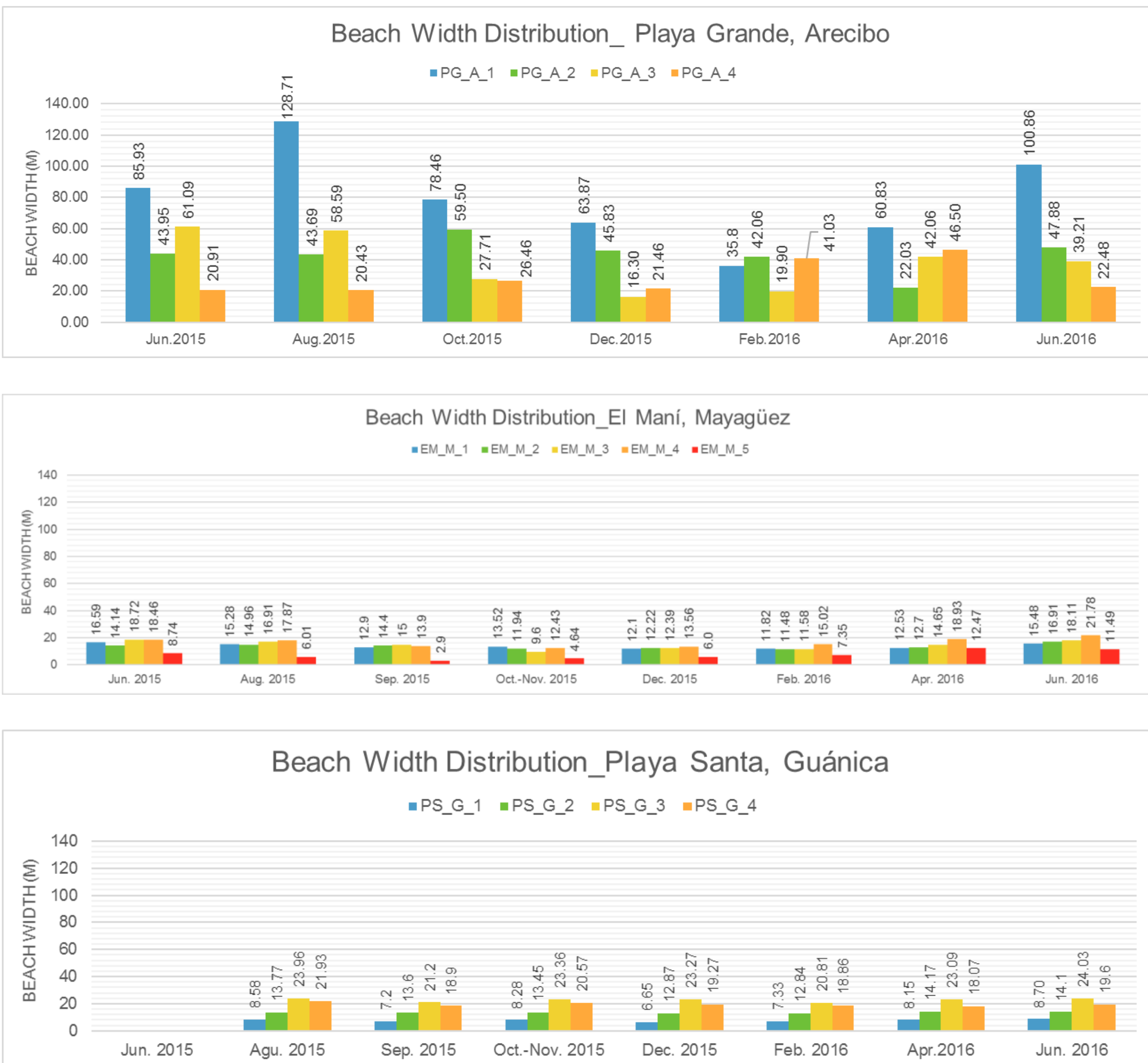


Figure 21. Beach width distribution at Playa Grande, El Maní and Playa Santa.

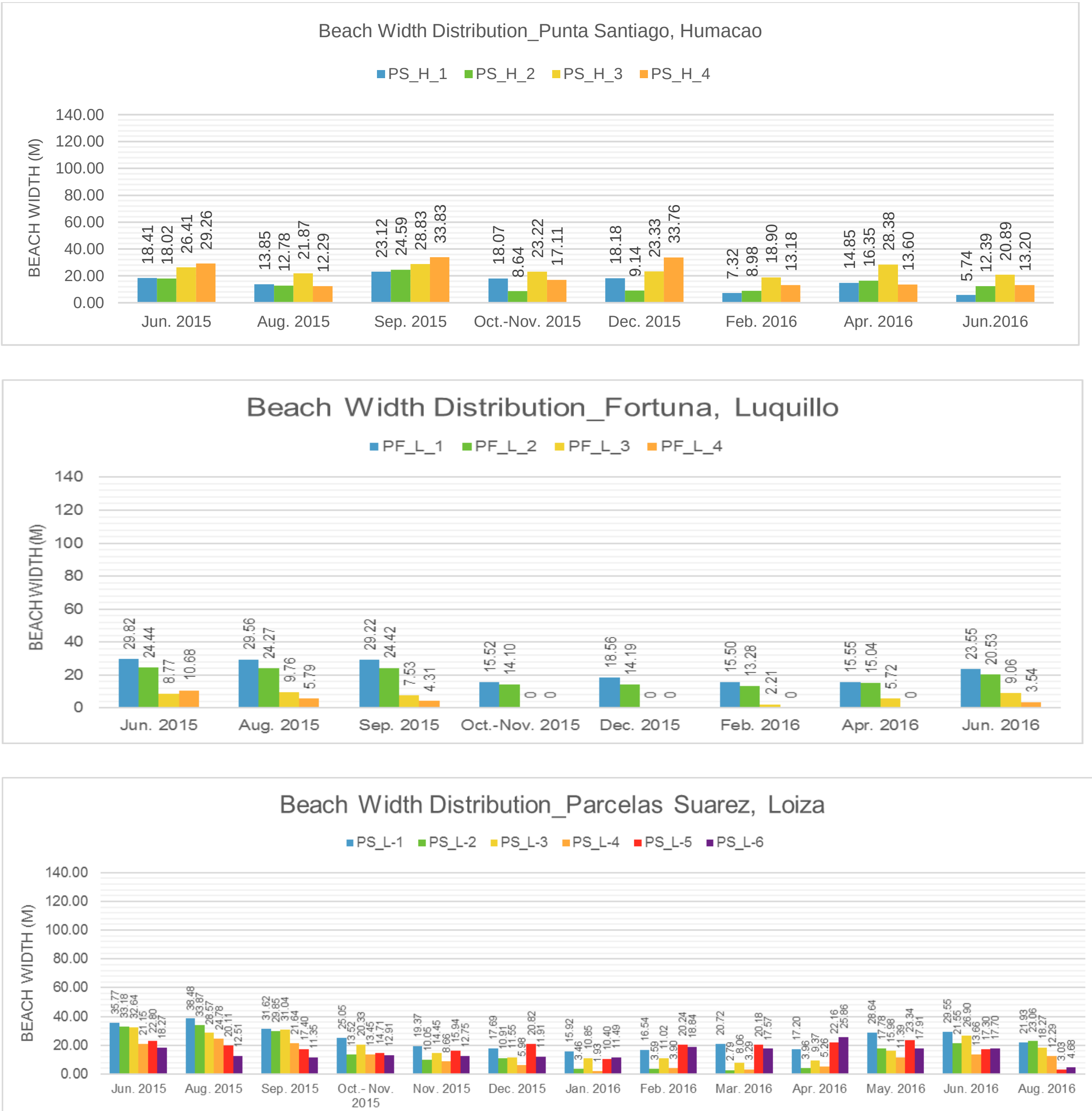


Figure 22. Beach width distribution at Punta Santiago, Fortuna and Parcelas Suárez.

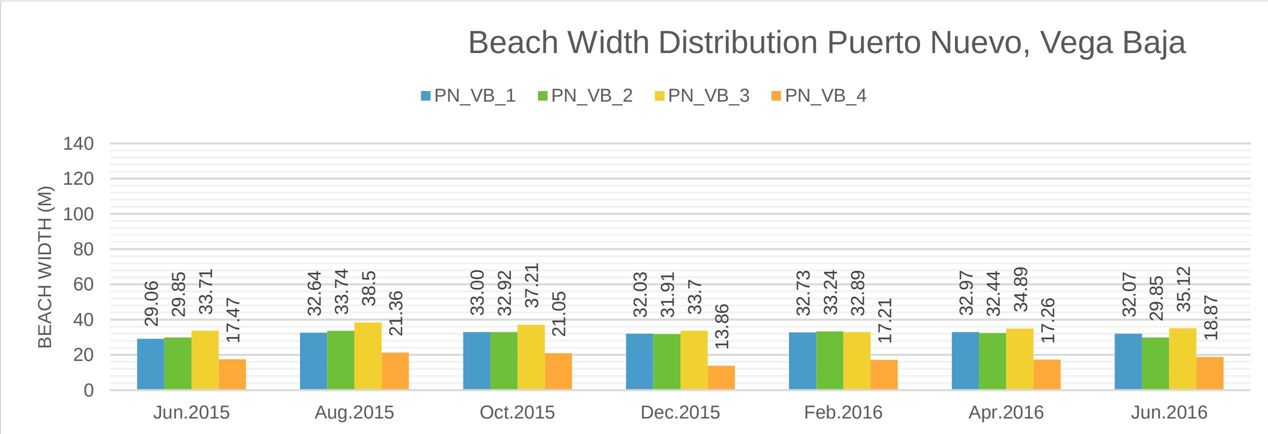


Figure 23. Beach width distribution at Puerto Nuevo, Vega Baja

4.4 Beach Profiles

Two hundred thirty (232) two beach profiles were surveyed from June 2015 to June 2016 to study the summer-winter seasonal cycle. In general, the beach had a convex profile shape with a berm build up and sediment accumulation above mean sea level during summer. In the winter, the beach lost the berm, which migrated offshore to form bar features. Usually, the volume of sediment removed from the profile above the mean sea level was equal to the volume of sediment deposited below the mean sea level, if the beach is in equilibrium stage. In this study was found that the majority of the studied beaches do not follow the regular summer-winter seasonal cycle. Playa Santa, Guánica is the unique beach system that follow the beach seasonal cycle in this study. Loss and gain of sand showed important variability in the majority of the stations and periods.

Playa Grande, Arecibo

Twenty eight (28) beach profiles were measured at Playa Grande, Arecibo from August 2015 to June 2016. Beach profiles showed variability in shapes, elevation and width between stations for the study period. Beach elevation and width differences may related with the coastal orientation between stations. The seasonal summer-winter cycle is not well defined in this beach base on the profiling data. As an example, an important sand accumulation was identified in station 1 during winter season related with the occurrence of swells associated with cold system events in the North Atlantic area. In addition, beach accretion was observed in the majority of the stations for June 2016, except station 3 where loss of sand was identified for the same period. This beach has the ability to reconstruct the profile in a short period.

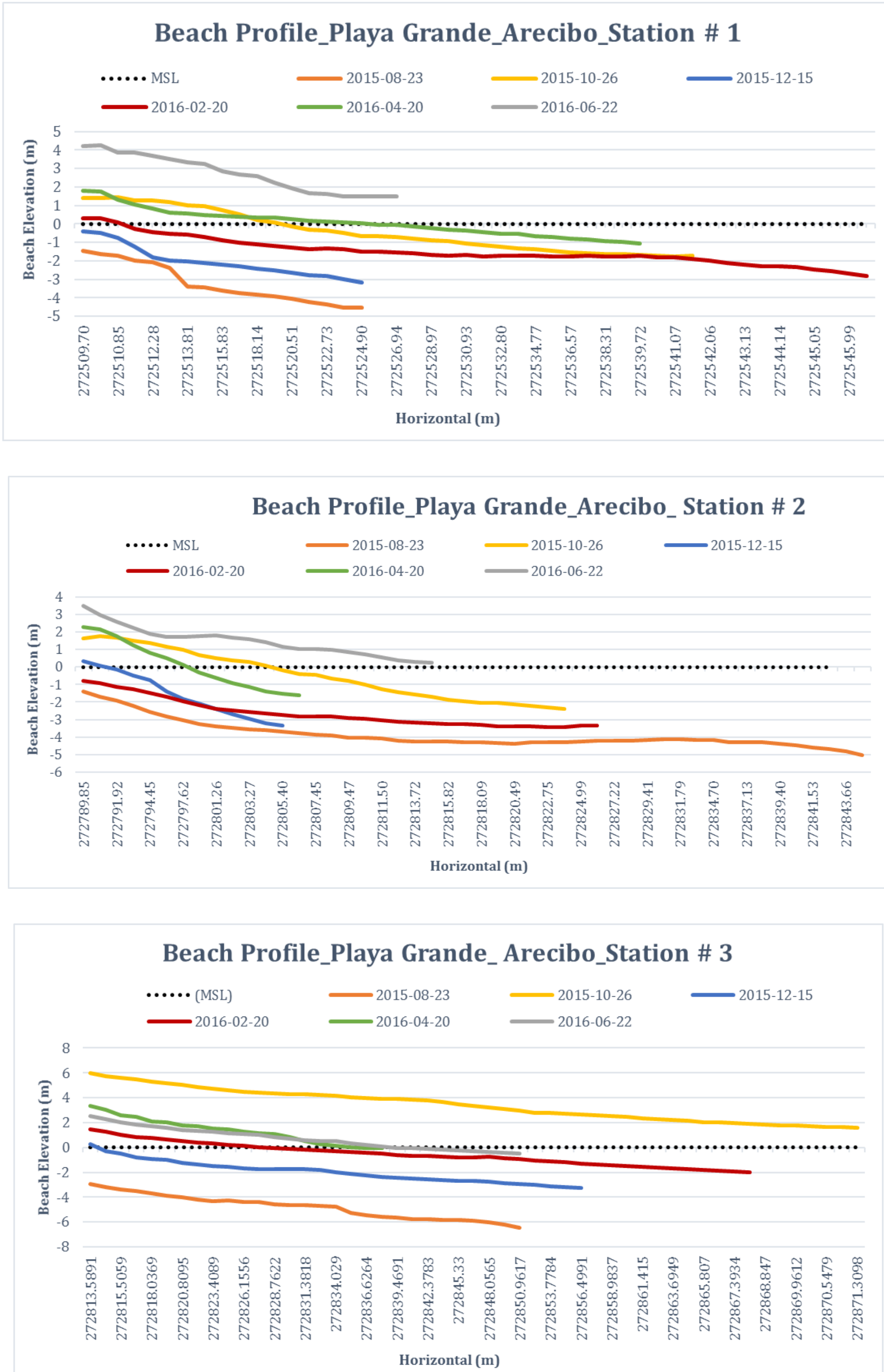


Figure 24. Beach profiles stations at Playa Grande, Arecibo

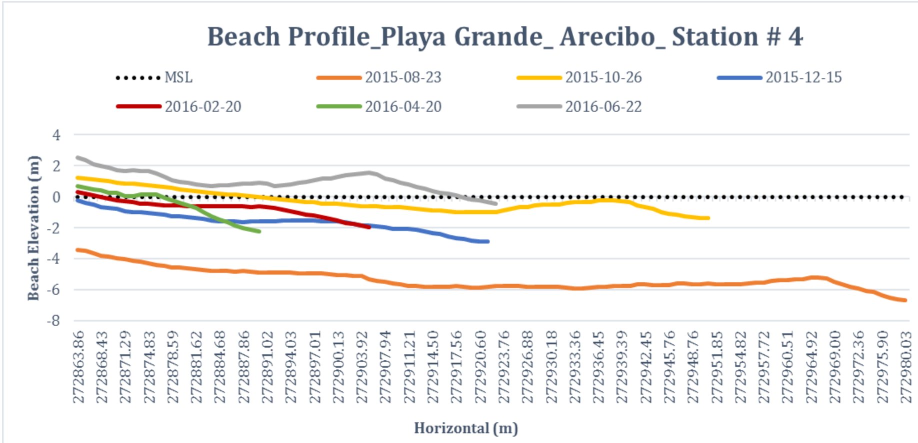


Figure 25. Beach profiles stations at Playa Grande, Arecibo

El Maní Beach

Forty (40) beach profile lines were survey from June 2015 to June 2016 period. The beach plain do not showed a seasonal summer-winter cycle. Beach elevation suffered many changes through the study period in all stations. Loss and gain of sand (vertical and horizontal) were identified during autumn and winter periods in the majority of the stations. Sand loss may related with swells associated with tropical storm with trajectories to the southwest of the Island and cold fronts. Important accretion was identified during winter

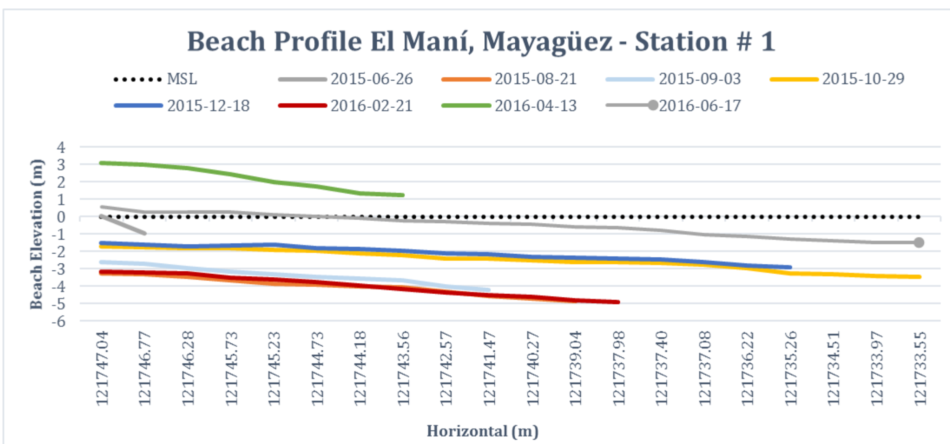
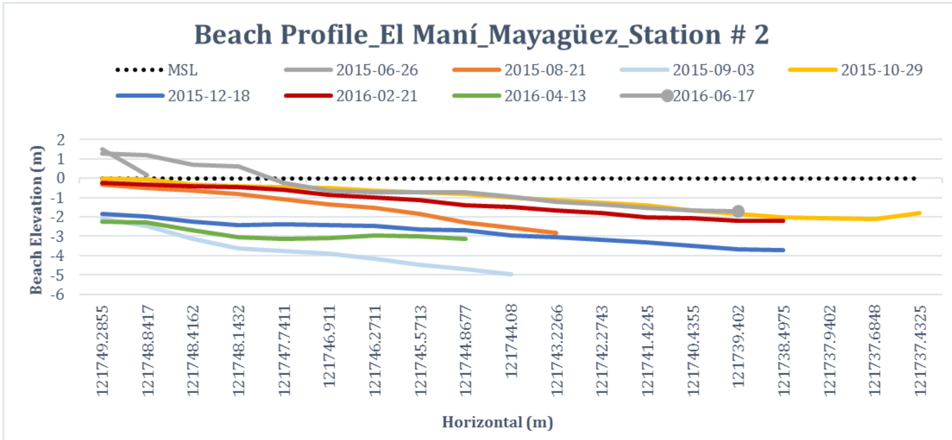
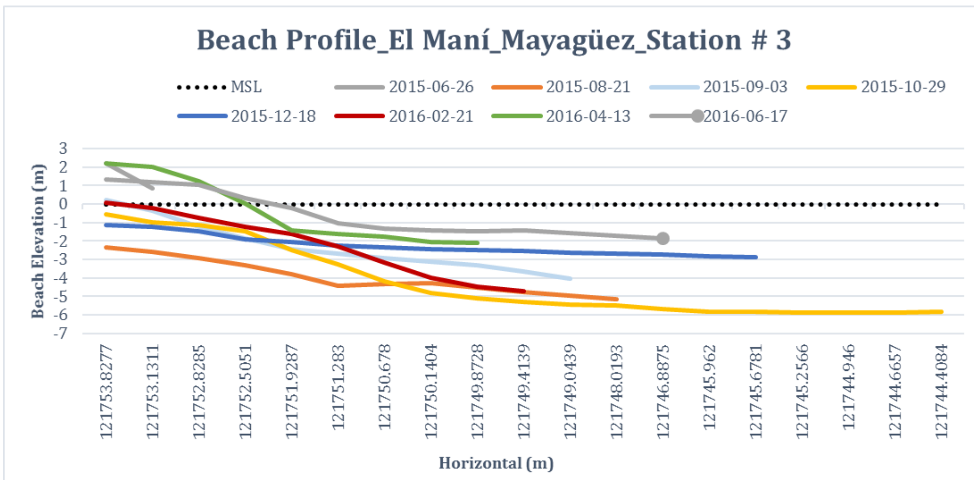


Figure 26. Beach profiles at El Maní, Mayaguez, PR.





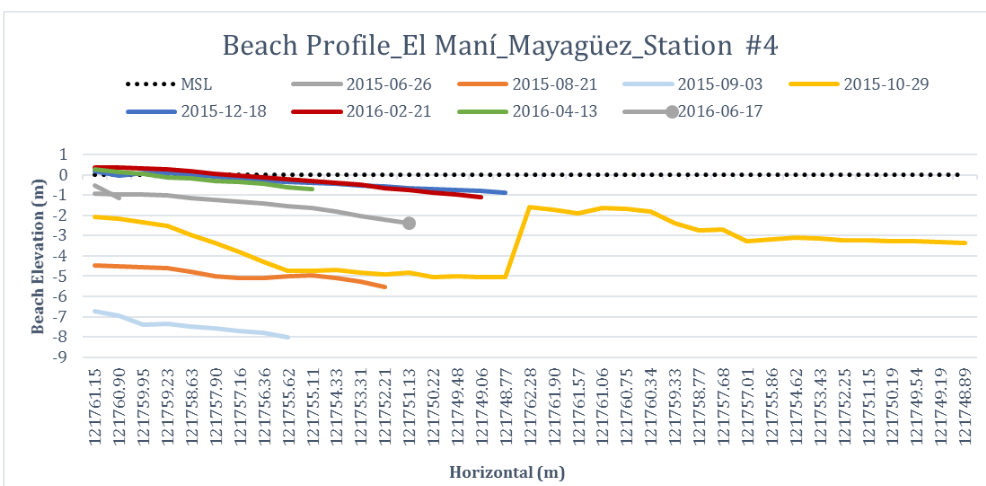


Figure 27. Beach profiles at El Maní, Mayaguez, PR.

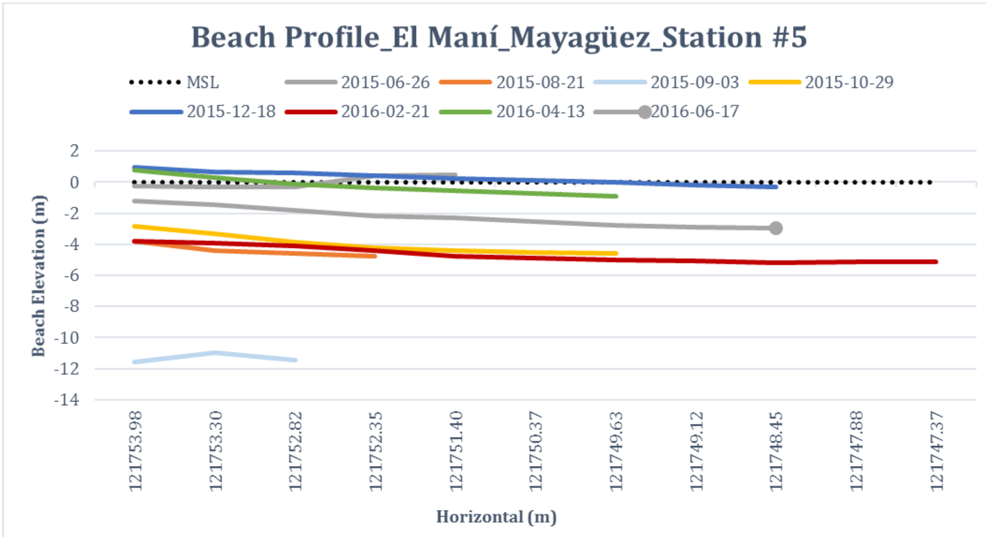


Figure 28. Beach Profile Stations at El Maní Beach, Mayaguez.

Playa Santa Beach, Guánica

Thirty two (32) beach profile lines were survey at Playa Santa Beach, Guánica from June 2015 to June 2016. This beach follow the seasonal summer-winter cycle in all stations. Accretion was observed during summer and loss of sand was identified during winter. The beach do not showed indicators of erosion problem in a small-scale period.

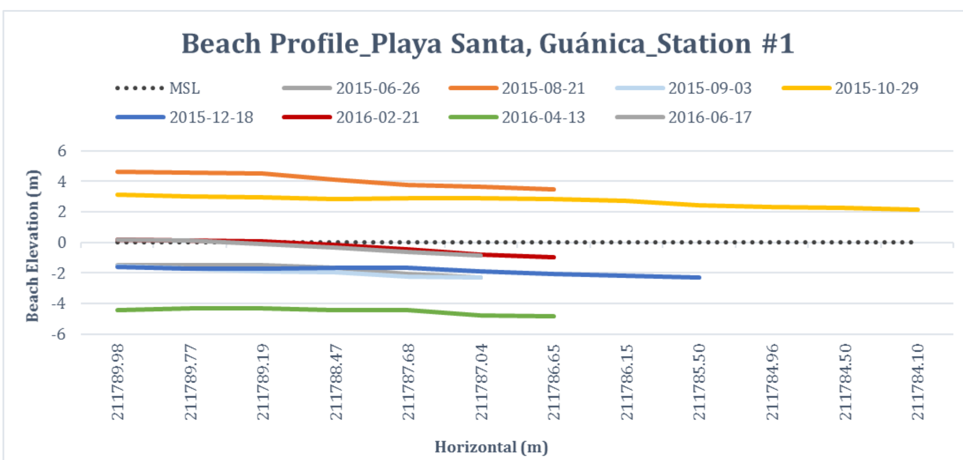


Figure 29. Beach profile at Playa Santa, Guánica.

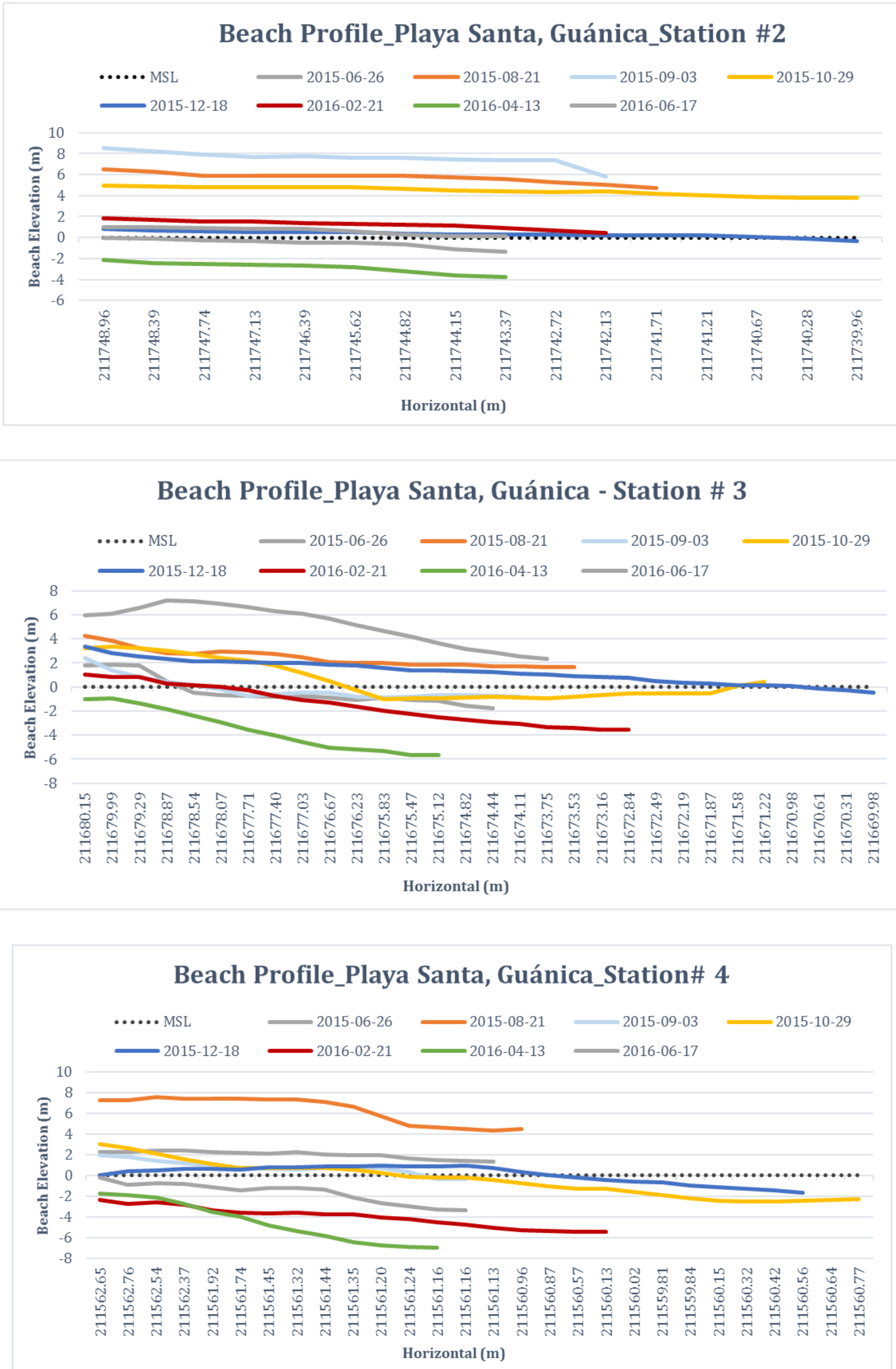
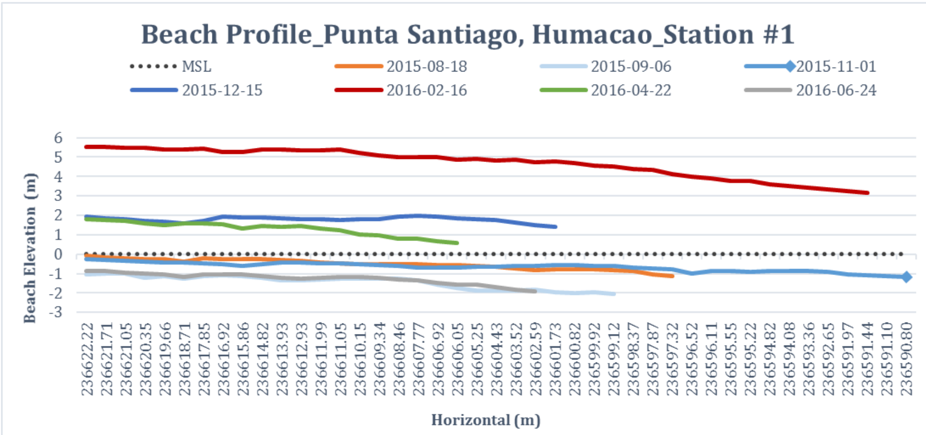
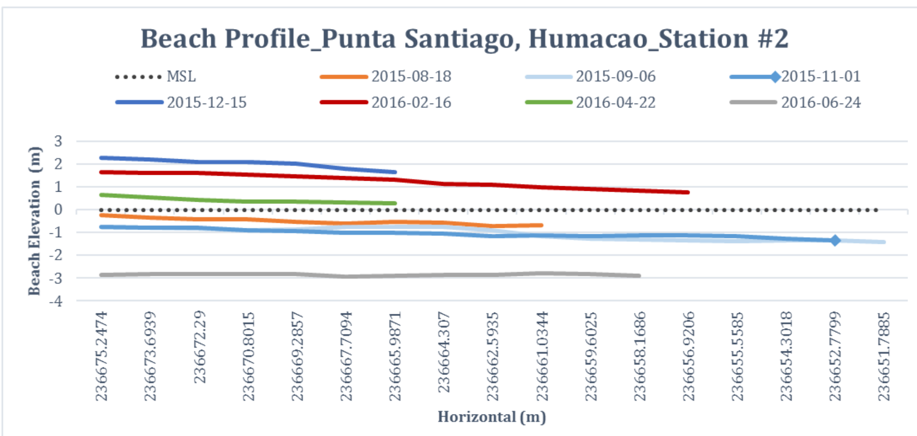


Figure 30. Beach profile at Playa Santa, Guánica

Punta Santiago Beach, Humacao

Twenty eight (28) beach profiles were surveyed from August 2015 to June 2016. The beach showed a flat topography with elevation variations in the majority of the stations through the study period. As well Playa Grande and El Maní, Punta Santiago beach do not fit the regular summer-winter beach cycle. Major sand deposits were found during winter in all stations.





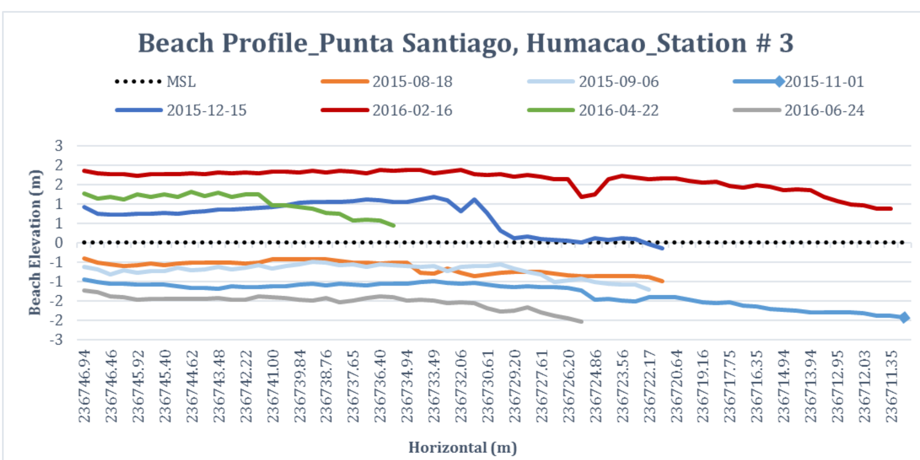


Figure 31. Beach profile at Punta Santiago, Humacao.

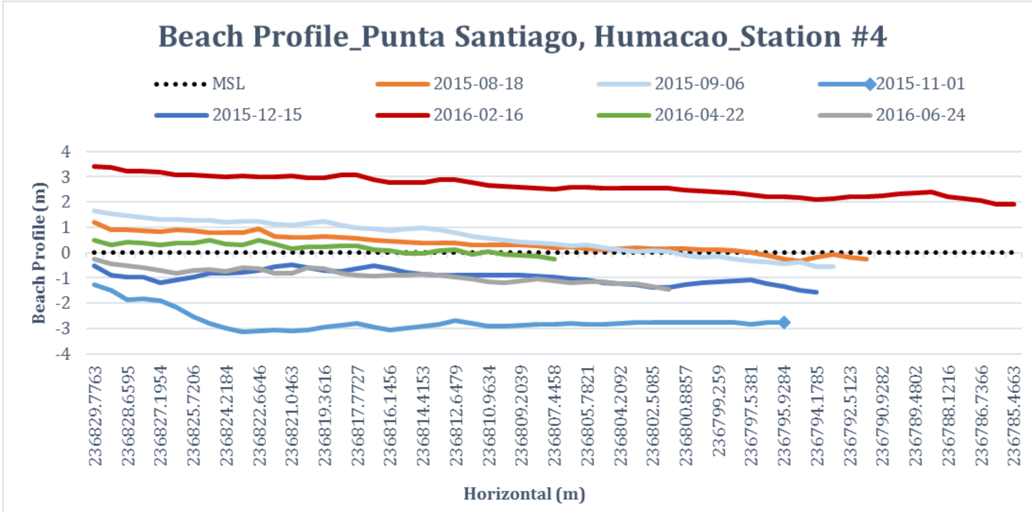


Figure 32. Beach profile at Punta Santiago, Humacao

Fortuna Beach, Luquillo

Twenty-eight beach profiles were surveyed at Fortuna Beach, Luquillo from August 2015 to June 2016. The beach do not follow the regular summer-winter cycle. During summer, the beach is wider and flat. During winter, beach elevation is higher than summer but showed shorter beach plains from station 1 to 2. Stations 3 and 4 showed major erosion problem along all year period. Major loss of sand was identified from November to April. This beach system is not recover from loss of sand especially in stations located to the west.

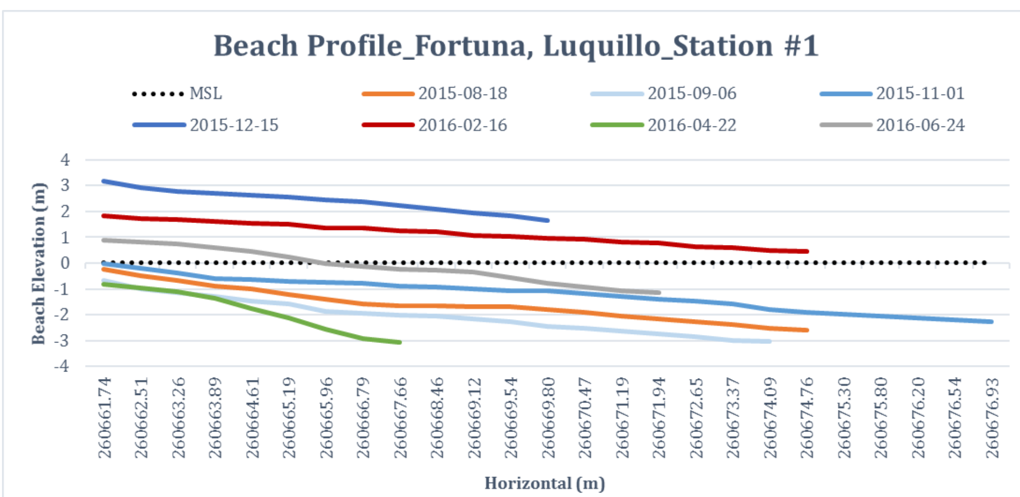
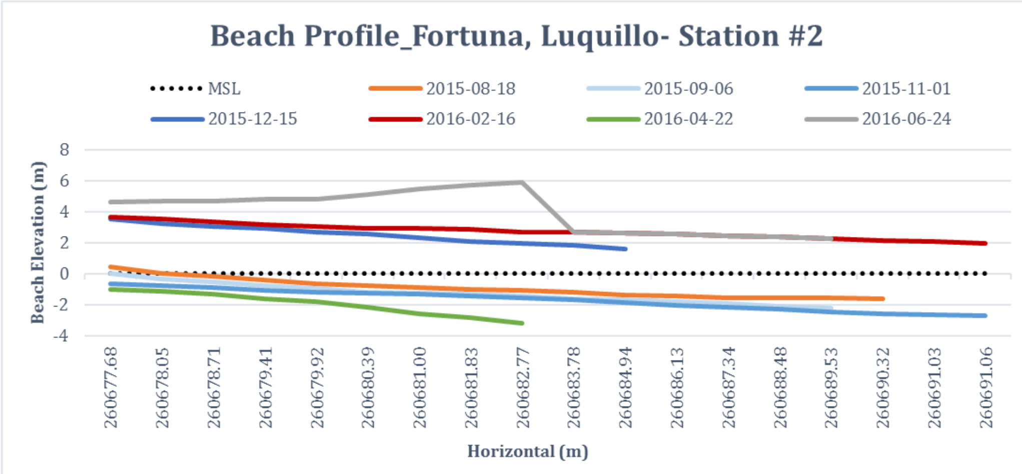
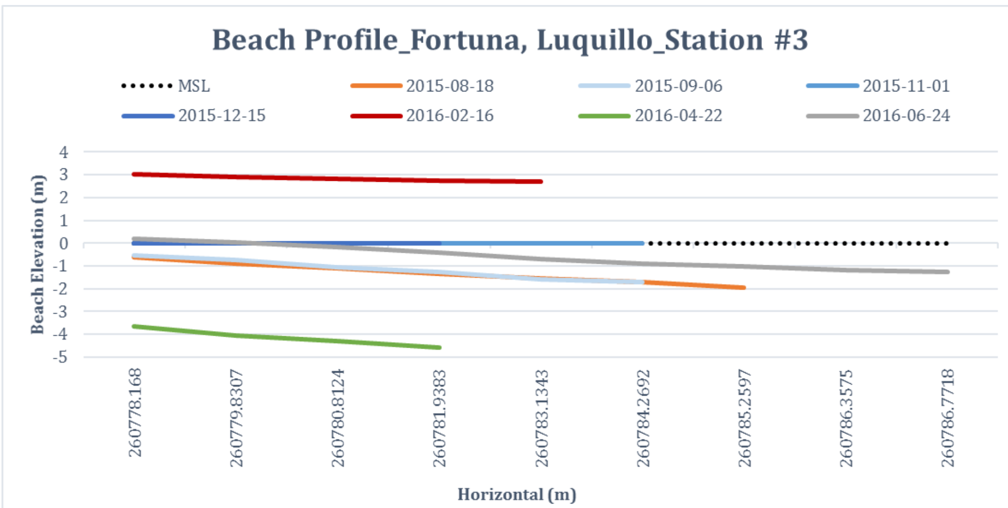


Figure 33. Beach profile at Fortuna Luquillo.





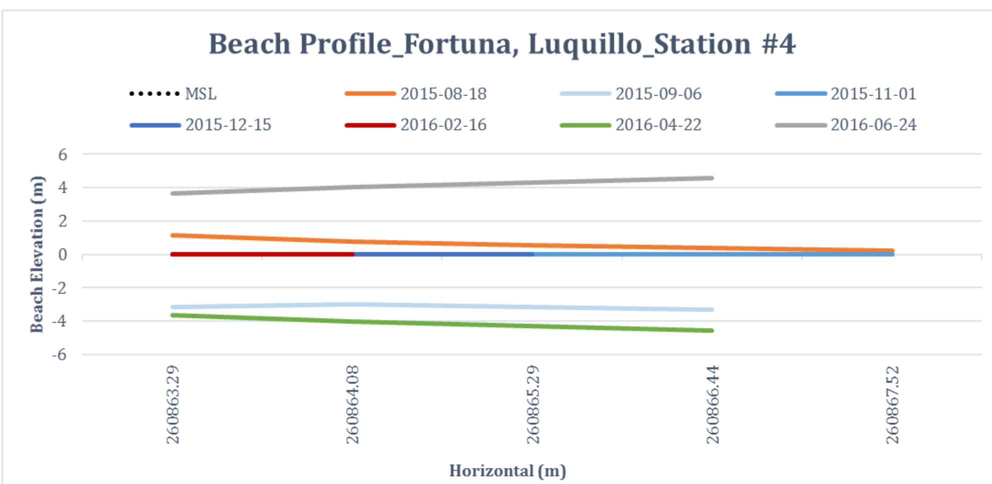
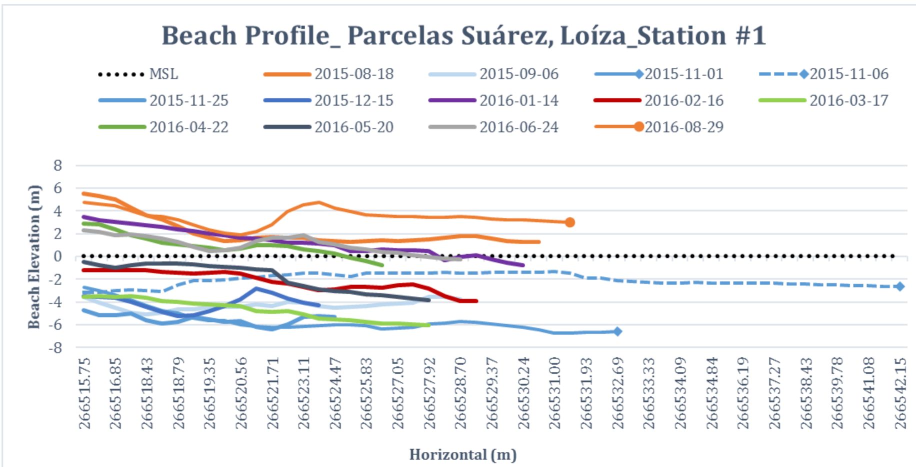


Figure 34. Beach profile at Fortuna, Luquillo

Parcelas Suárez, Loíza

Seventy six profile lines were surveyed at Parcelas Suárez Beach, Loíza from August 2015 to August 2016. Profiling studies were done in monthly basis due to the erosion problem identify in this site. According to profiling evaluation, the beach may divided in two main geomorphic sectors. These are the eastern and western site of the beach. Differences between these two geomorphic cells may related with the beach orientation. The eastern beach sector covered from station 1 to 3. This site showed beach plains with northwest and north orientation. The western beach cell includes from stations 4 to 6. This beach plain shows north and northeast orientation. Annual beach assessment indicated an erosion/accretion shits between eastern and western beach sectors. Beach profile changes do not follow the regular summer/winter cycle. Beach profile variability is evident between stations and periods.



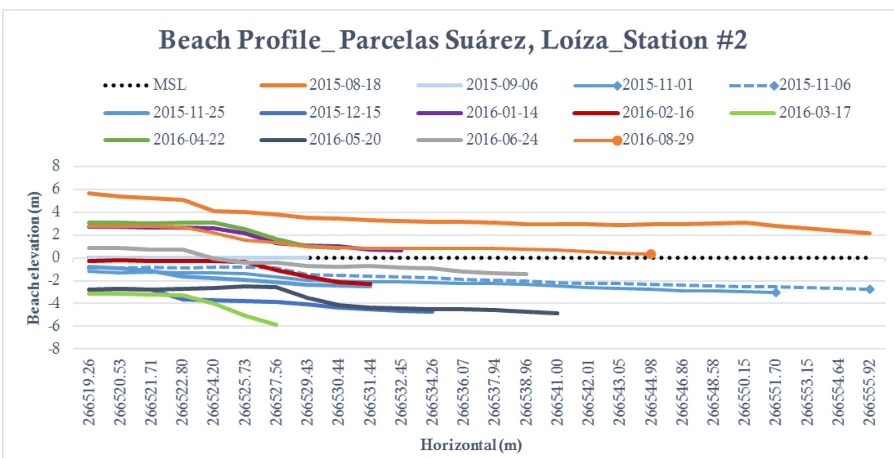


Figure 35. Beach profile at Parcelas Suárez, Loíza.

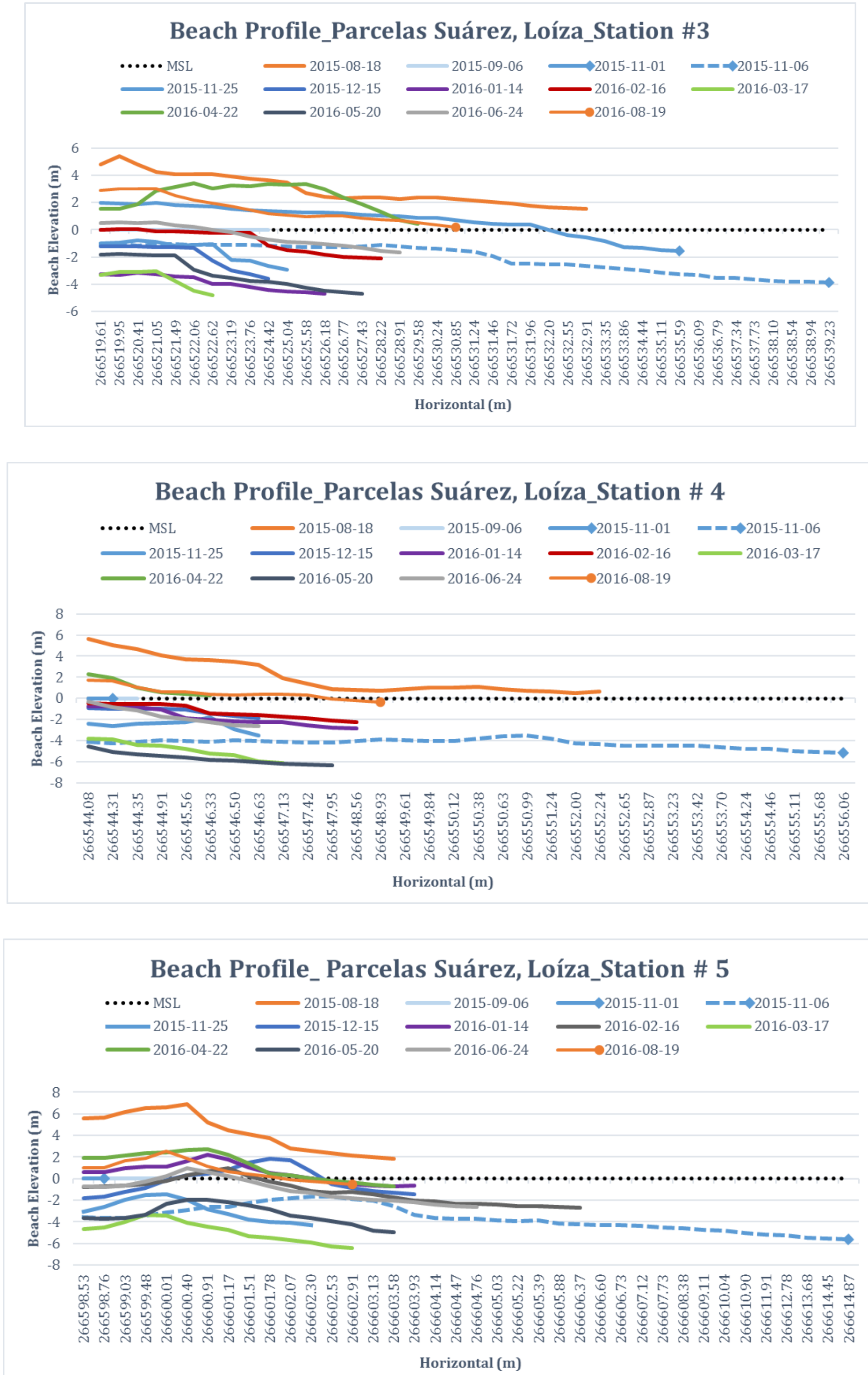


Figure 36. Beach profile at. Parcelas Suárez, Loíza

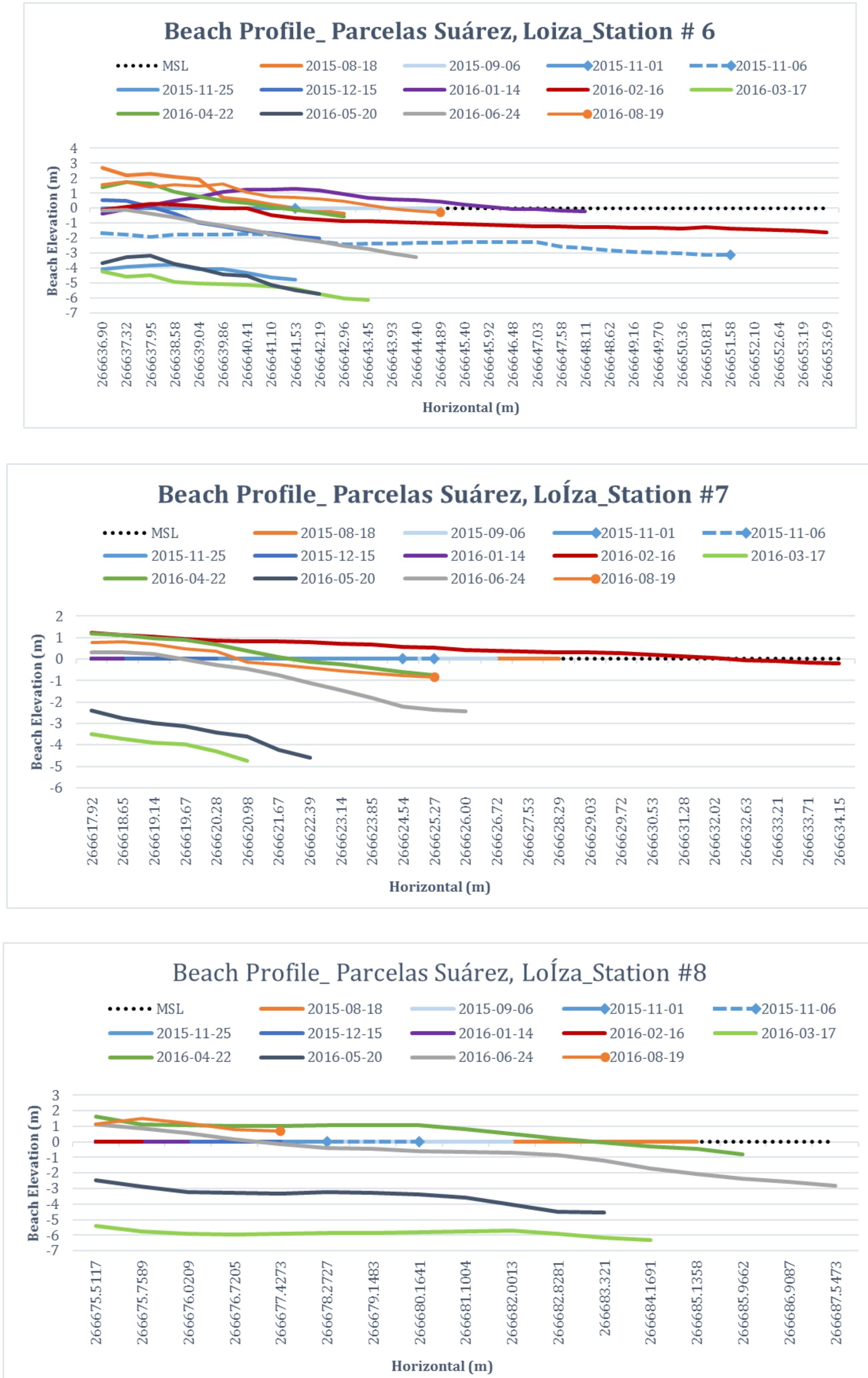


Figure 37. Beach profile at Parcelas Suárez, Loíza

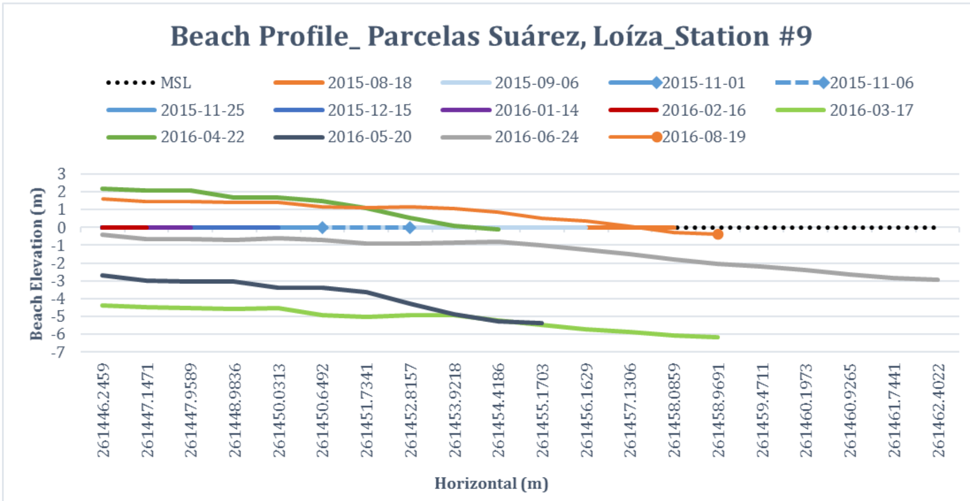


Figure 38. Beach profiles at Parcelas Suárez, Loíza

Puerto Nuevo Beach, Vega Baja

Twenty eight (28) beach profile stations were measured at Puerto Nuevo beach, Vega Baja from August 2015 to June 2018. Profiling behavior do not follow the regular seasonal summer-winter cycle in all stations. The beach cycle is shifted with gain of sand during winter and loss of elevation during summer. Major beach profile changes were observed in station 4 where loss of sand was identified through study period. Station 4 is not protected by natural barrier Minor profile changes were found in station 2 during study period. This may related by the presence of eolianite that produce protection to the beach.

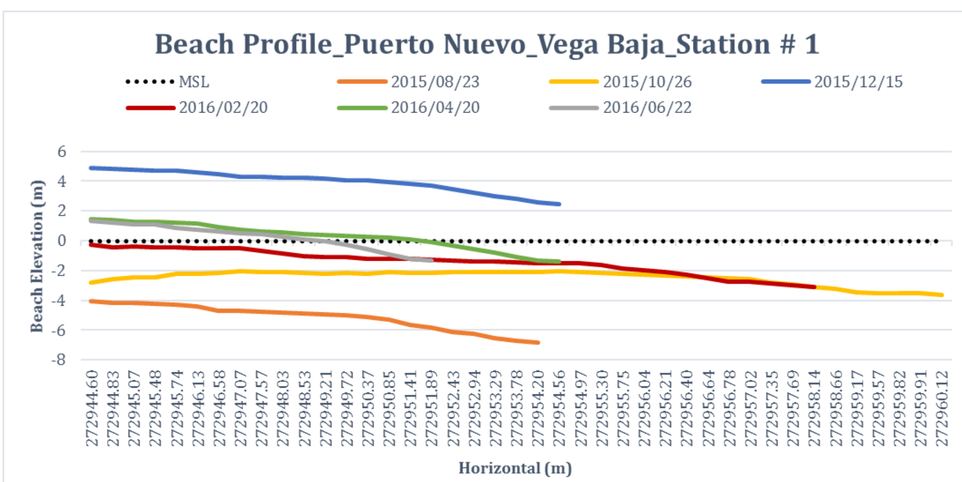
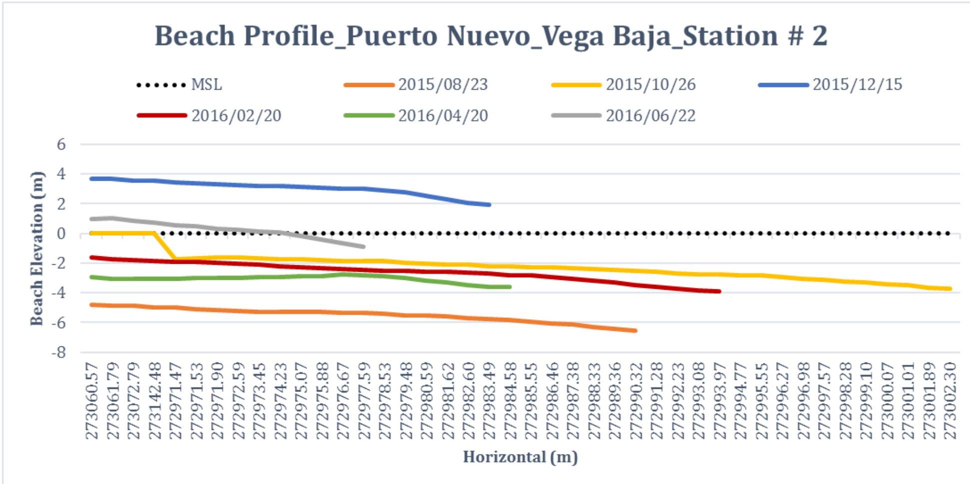
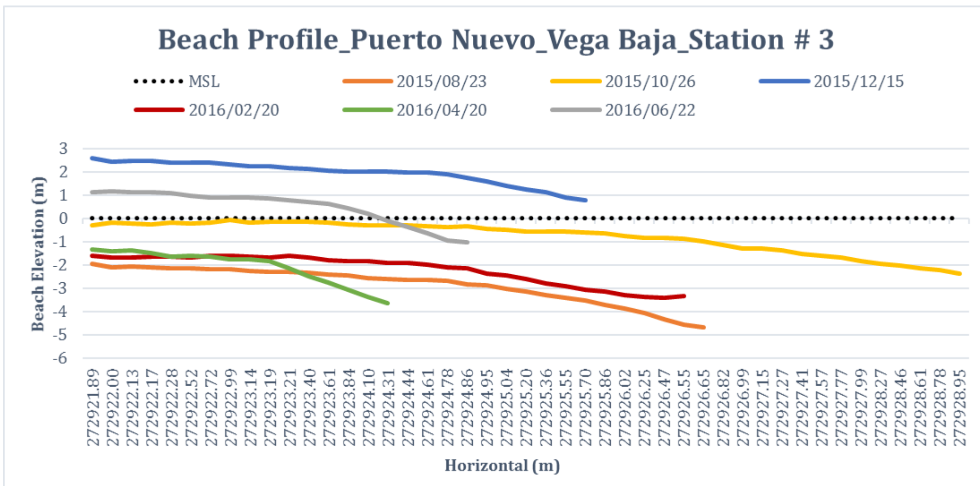


Figure 39. Beach profile at Puerto Nuevo, Vega Baja.





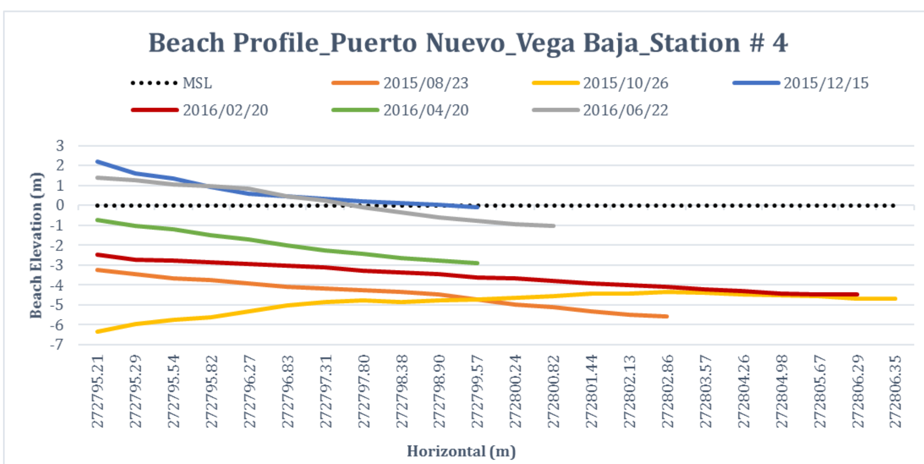


Figure 40. Beach profile at Puerto Nuevo, Vega Baja.

4.5 Beach sediment composition

Five hundred seventeen (517) beach sediment samples were collected and analyzed to identify beach sediment composition. Three sediment components were identified in beach sites included in this study. These are biogenic (≥75% calcium carbonate component), terrigenous (≥ terrigenous component as minerals/rock fragments) and mixed biogenic and terrigenous sediments (between 26 to 74 % both components). Carbonate biogenic sands came from biogenic production, including spicules, forams, coral fragment, carbonate seaweeds and molluscan shell debris. Biogenic sands were found at Playa Santa (Guánica) and Fortuna Beach (Luquillo). Terrinenous sands came from the erosion of terrestrial rock that can transported from different source distances through river sediment transportation. Terrigenous beaches were identified at El Maní, Mayaguez and Punta Santiago (Humacao). Mixed carbonate and terrigenous sand beaches are found at Playa Grande (Arecibo) and Playa Puerto Nuevo (Vega Baja). Parcelas Suárez showed two separate beach section based on sediment composition. These are: a mixed carbonate and terrigenous beach (station 1, 3 and 4) and terrigenous beach (stations 2, 5, 6 and 8). Differences in sediment composition were identified between backbeach and swash zone in some of the study sites.

Figure 41. Beach Sediment Composition by station at Playa Grande, Arecibo, Puerto Rico (2015-16)

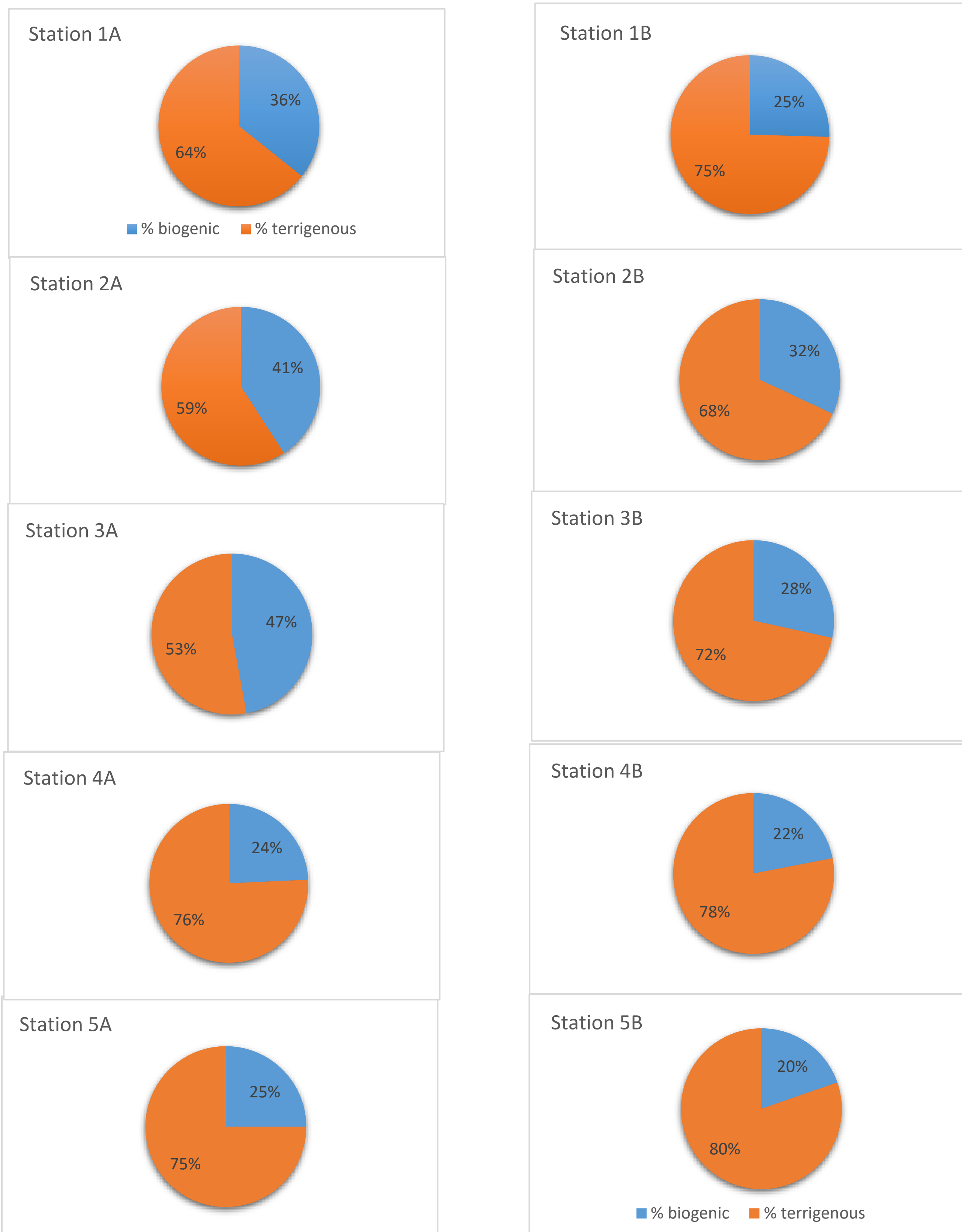


Figure 42. Beach Sediment Composition by station at Playa El Maní, Mayaguez, Puerto Rico (2015-16)

Figure 43. Beach Sediment Composition by station at Playa Santa, Guánica, Puerto Rico (2015-16)

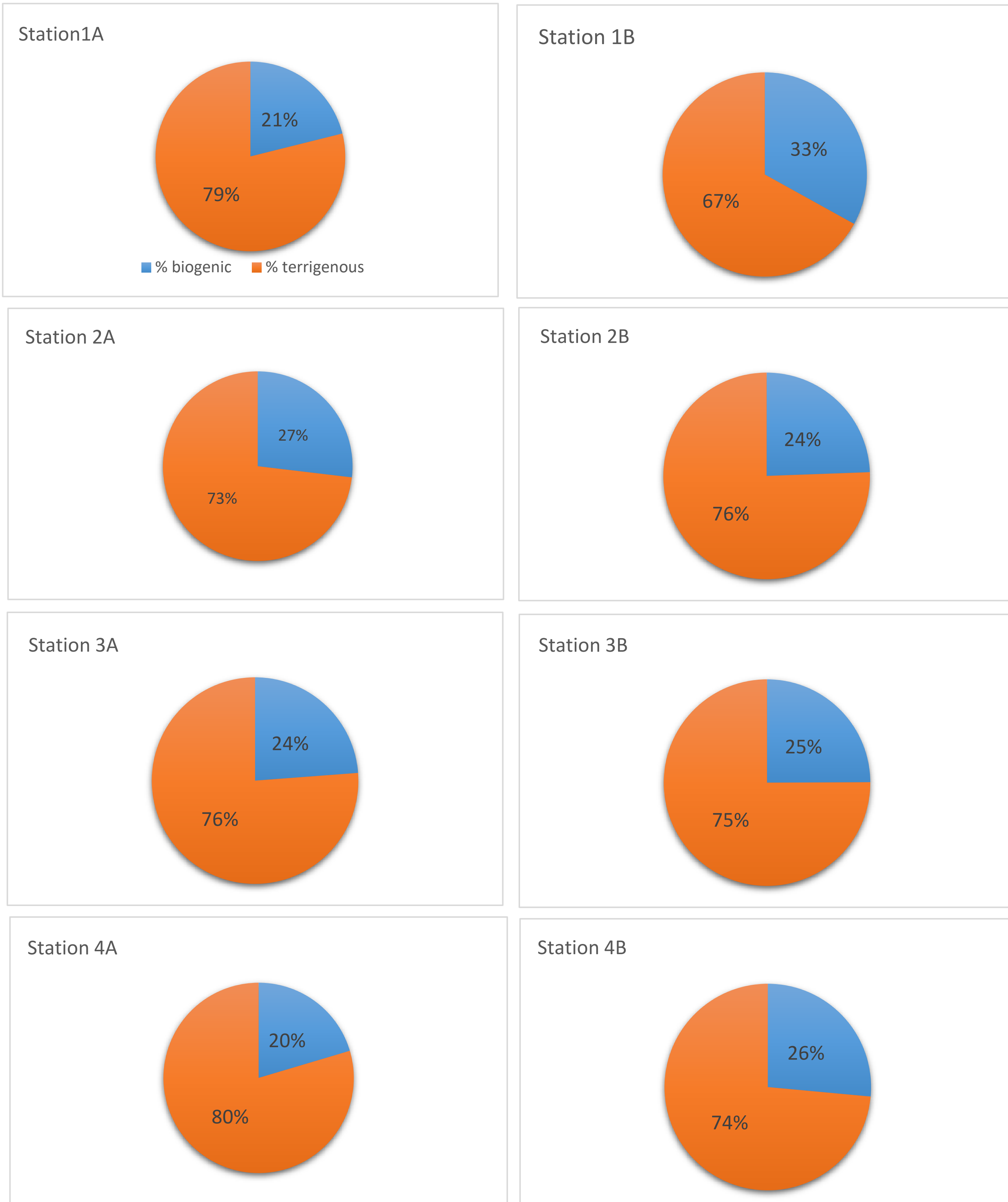
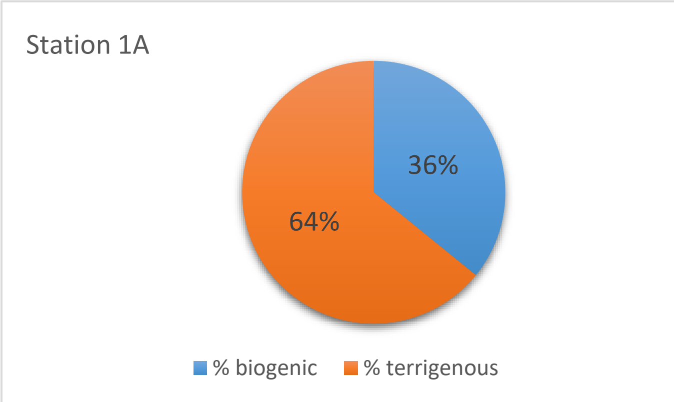
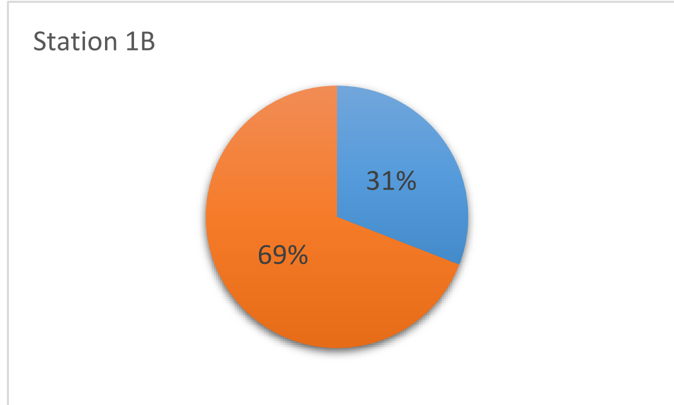
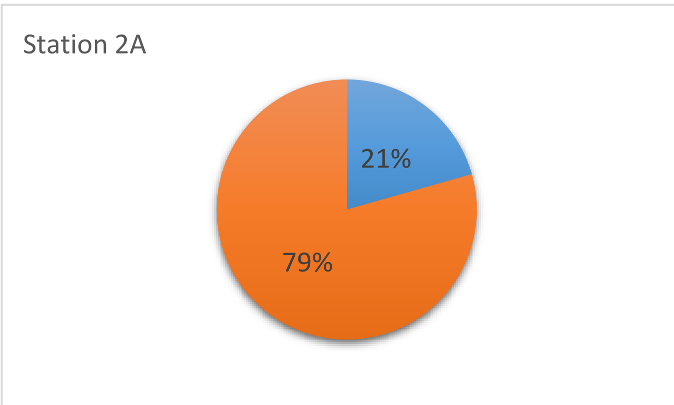


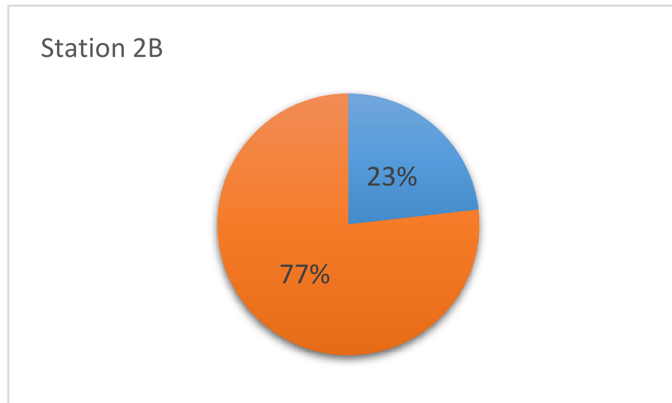
Figure 44. Beach Sediment Composition by station at Playa Punta Snatiago, Humacao, Puerto Rico (2015-16)

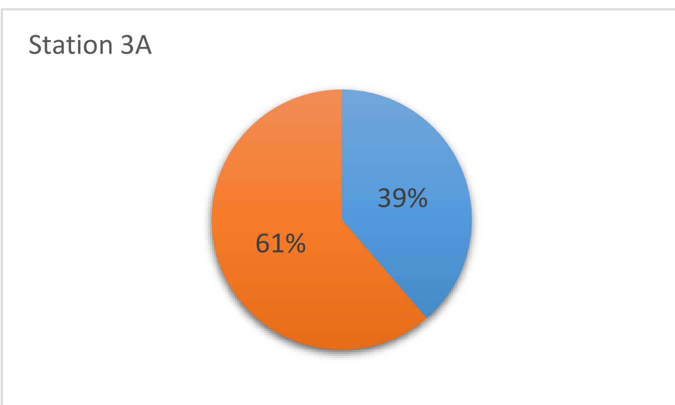
Figure 45. Beach Sediment Composition by station at Playa Fortuna, Luquillo, Puerto Rico (2015-16)

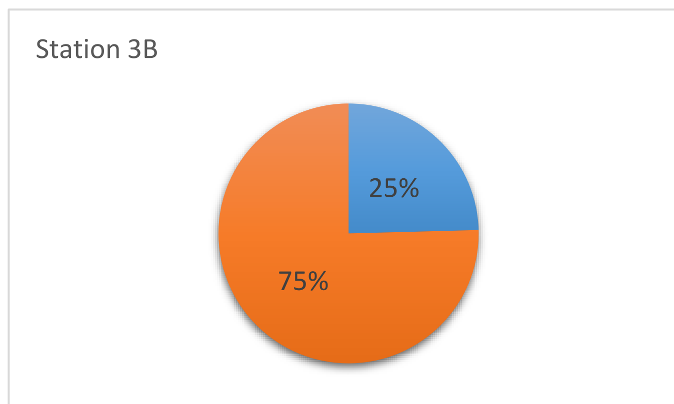

Station 1A
36%
64%
% biogenic
% terrigenous

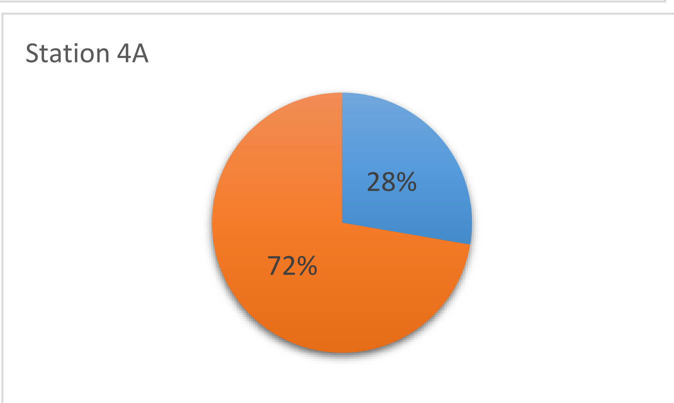

Station 1B
31%
69%

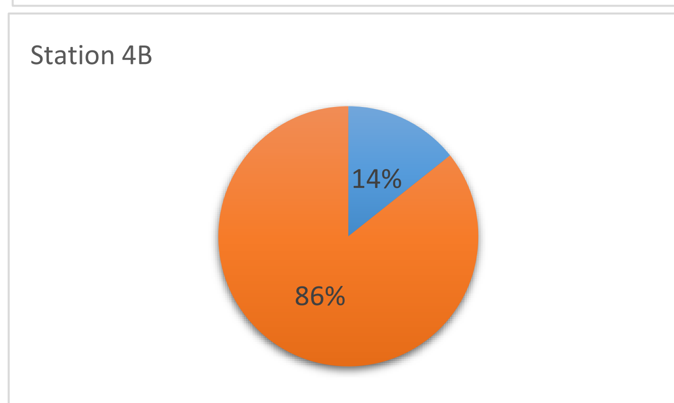

Station 2A
21%
79%

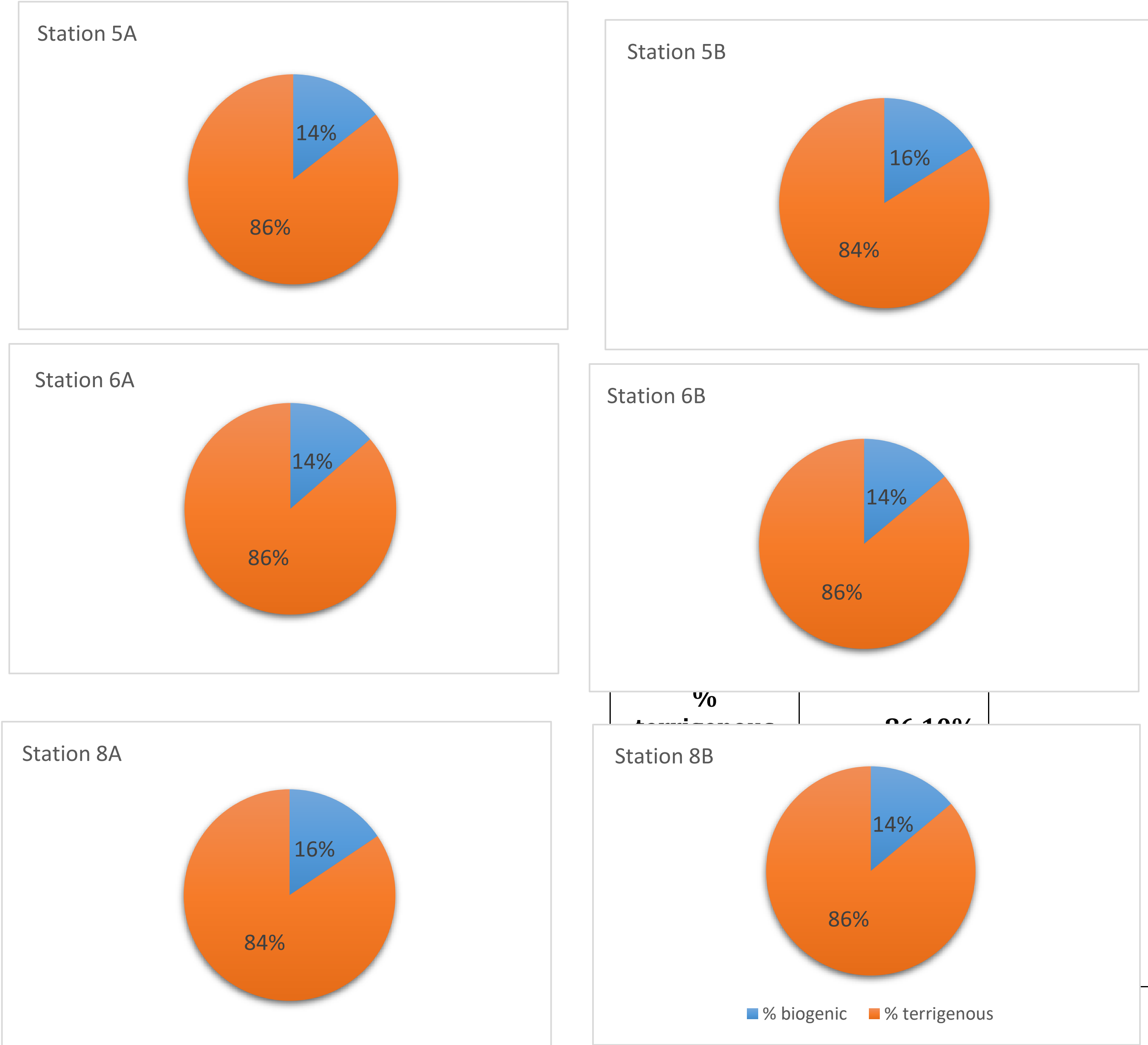

Station 2B
23%
77%


Station 3A
39%
61%


Station 3B
25%
75%


Station 4A
28%
72%


Station 4B
14%
86%



Parcelas Suárez Beach Sediment Composition 8B

Figure 46. Beach Sediment Composition by station at Playa Parcelas Suárez, Loíza, Puerto Rico (2015-16)

Figure 47. Beach Sediment Composition by station at Playa Puerto Nuevo, Vega Baja, Puerto Rico (2015-16)

5. Conclusion

1. Beaches is the more occurring coastal type of the Island of Puerto Rico.
2. Approximately, 1,225 beaches are identified along the coastline using remote sensing techniques for 2010.
3. Major beach orientation of beaches included in this study are from north-west, north and northeast. These beaches are located on the north, west and east coast of the Island.
4. An overview of shoreline changes showed a variety of erosion and accretion along the Puerto Rico coastline position from 1970's to 2010.
5. Loss of sand is the major event found in the majority of beaches from 1970's to 2010. Approximately, 60% of the beaches included in this study suffered erosion in Puerto Rico for this period.
6. Accretion is identified in 40% of the beaches in the Island.
7. More stables beach sites are located at Patillas, Barceloneta, Ceiba, Maunabo from 1970's to 2010.
8. Major accretion rates were identified in beach transects at Arroyo (2.30 m/yr), Salinas (3.8 m/yr), Ponce (1.76 m/yr), Camuy (1.62 m/yr), Yabucoa (1.65 m/yr), Hatillo (1.29 m/yr) and Arecibo (1.24 m/yr).
9. Major loss of sand was identified at Dorado (-1.94 m/yr), Loíza (-1.93 m/yr), Arroyo (-1.28 m/yr), Toa Baja (-1.40 m/yr), San Juan (-1.21 m/yr).
10. Continuous beach profile changes were evident in all beaches included in this study. Major beaches included in this study do not follow the regular seasonal summer/winter beach cycle.
11. Major beach profile changes (elevation and width) were measure at Parcelas Suárez (Loíza), Playa Fortuna (Luquillo) and Playa Grande (Arecibo).
12. Erosion problems is observed mainly at Parcelas Suárez (Loíza) and Playa Fortuna (Luquillo).
13. Minor beach profile changes were measured at Playa Santa, Guánica.
14. It is evident the important role of natural barriers protecting the beach profiles evaluated.
15. Biogenic, terrigenous and mixed (Biogenic and terrigenous) beach sediments were identified in beaches included in this study.

Recommendations

1. We recommend conducting the historical shoreline changes assessment for 2016-2017 period for the Island. The preparation of the 2016 shoreline feature will be valuable to calculate actual shoreline changes rates at the Island. High spatial resolution images are available to identify this new shoreline scenario (commercial images). This information will helpful to the coastal decision making process.

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