ENVI and Arc GIS to Detect Beach Morphology from Three Beaches in Isabela, Puerto Rico

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ABSTRACT

Shorelines are important natural features that serve an important function economically for nations worldwide. As such every effort should be made to understand and conserve these features that are increasing falling victim to erosion by anthropogenic effects associated with coastal development. Along Puerto Rico's north coast destruction of the system of dunes was underway in the 1960s. Subsequent development on the coastline has predictably led to coastal erosion however efforts to restore wetlands and the end of widespread agricultural practice has also led to aggregation of the coastal zone as well. Three beaches in the Isabela area were chosen to analyze changes in the shoreline: Playas Jobos, Montones, and Sardinera. By comparing historical aerial photos from the 1930s and using modern Satellite images and GPS field data a comparison can be made utilizing the ENVI and Arc GIS software to determine where and to what extent the shoreline has been accreting or eroding.

KEYWORDS

Shoreline, geomorphology, Coastal, sedimentation, erosion

INTRODUCTION

Coastal areas and beaches are important natural and economic resource. Data from NOAAs office for coastal Management show that inn the US alone 10% of US land mass is located within the coastal zones, though it is inhabited by 40% of the population, or 126 million people. The counties adjacent to the coast produce $8.3 trillion worth of goods and services annually contributing 56 million jobs that amount to $3.4 trillion in wages annually. Clearly the areas adjacent to the coast are important to our wellbeing and it is important to understand the processes that may negatively impact them.

With so much at stake many researchers have turned their attention to monitoring our coastlines. Data gathered paints a very grim picture of the state of our coastlines. Some studies show that 80-85% of the Earth's shorelines are retreating due to loss of sediment supply (Pilkey, et. al. 2009). Rates of loss along the shoreline are occurring at 1 m, +/- 0.5 m per year (Pilkey et. al., 2009), which is largely an anthropogenic effect caused by the damming of rivers, armoring of shorelines, and dredging of navigation channels which could conceivably result in complete and total destruction of beaches in 40-50 years' time (Pilkey et. al. 2014). These rates have been confirmed within Puerto Rico following a 70-year study by the USGS along the coast of Rincon from 1936-2006. The Digital Shore-line Analysis System (DSAS) employed remote sensing techniques to track changes for this time period and led to the conclusion that the shoreline was rapidly retreating at rates comparable to Pilkey et. al. (2009) and that the erosion was both a product of natural processes and an artifice of human actions. (Thieler et. al. 2007).

While some might doubt the extreme pessimism of the conclusion by Pilkey et. al (2014), certainly there is a recognizable existential threat to our shorelines due to anthropogenic effects. Others might counter the argument that our shorelines are certain to be destroyed outright. While construction near or on the shoreline can 'reduce the natural flexibility of the beach' (Bush et. al, 1995), it was noted that natural shoreline erosion is a common event and is not a threat to the coast, but an integral part of coastal evolution and does not mean that the beach is disappearing, but simply changing its location.

While one might debate the eventual fate of our beaches, it is clear that we must monitor them going forward. An attempt to archive shoreline positions should be widely begun to better determine if there will be some existential threat to our shorelines in the future. Certainly human activity is having an impact on the coastline of Puerto Rico and degrading, to some extent, the coastlines as evidenced in the study by Thieler et. al. (1995), but here have also been efforts by the Department of Natural Resources and Ambientales (DNRA) to restore wetlands along the coast and can be seen as an attempt to restore the 'natural flexibility' of the coastline. \

Figure 2 Dunes at Isabela

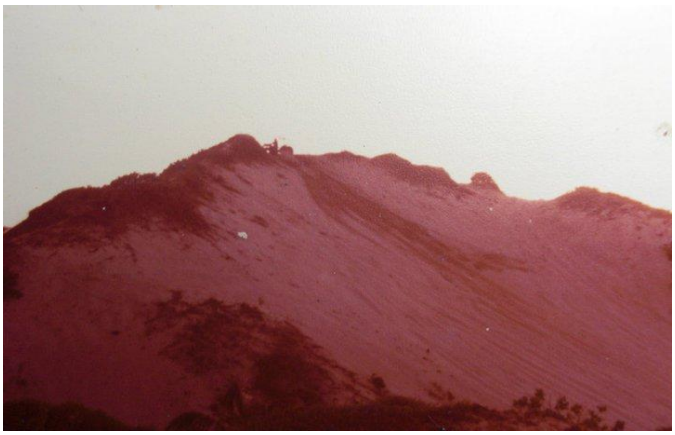


Figure 1 Dunes along the north coast around Isabela towering to 30 m high

The north coast of Puerto Rico is classified as a storm coast because it is subject to wind and wave effects that has a dominant effect on its geomorphology (Beirman and Montgomery, 2014). The coast is subject to punishing winter storms, termed "Nor'easters" as the originate from the Atlantic from the months of October to April and can produce waves with heights of over 15 feet and periods of 17 seconds. Typical wind patterns for the region are the north east trade winds. Both wind and waves have a powerful morphological effect on this coast and significantly shift sand around the littoral zone. It was certainly an effect of a large sediment supply and strong winds that grew, over millennium, the tall sand dunes which once ranged from Areceibo to Isabela and grew to enormities up to 30 m in height (Figures 1 & 2).

Dunes are important feature on storm coasts as they are deep reservoirs of sediment which help preserve sand within the system and act as buffers against rising sea level heights (Beirman & Montgomery, 2014). Figures 3 shows a typical storm coast where sediments washed offshore during seasonal storms will be deposited again during calmer conditions. A large dune system preserves the sediments within the system which are mobilized during these extreme events, without dunes providing a reservoir of sediment, the beach will eventual thin as the storm berm is eroded away (Beirman & Montgomery, 2014). The great dunes of the northwest coast were subsequently mined wholesale during the 1960s (Figure 5 & 6) and it has yet to be determined if this has had any long term effect on the shorelines of these coasts.

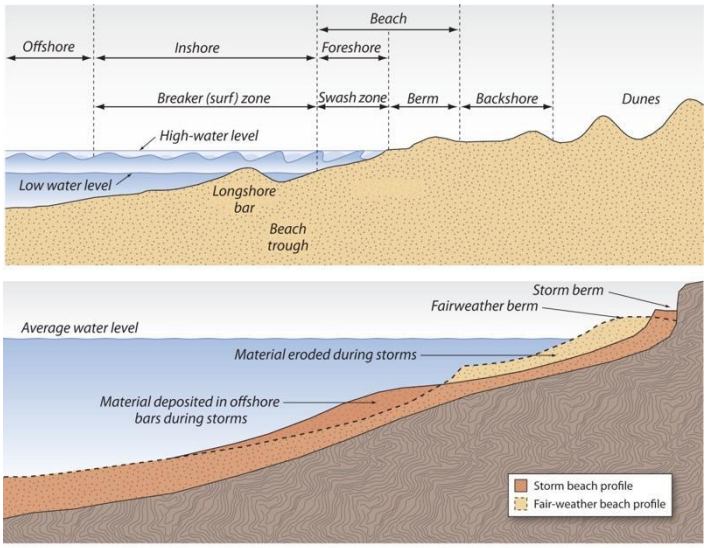


Figure 3 Cartoon showing a healthy beach with a dune (top) that serves to preserve sediments within the system (Beirman & Montgomery, 2014).

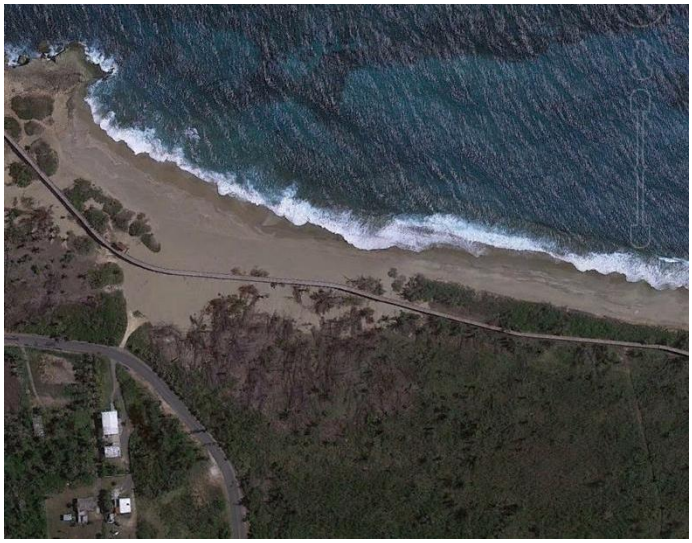


Figure 4 Playa Montones showing break in the dunes where washover is causing sediment to escape the beach system.

The objective of this study is to determine the long term effect that mass removal of the dunes around Isabella has had on the current shoreline. Damage to the dunes is causing a loss in the sediment reserves of the beach. For example, Figure 4 shows Montones beach where a break in the dunes is now seeing washover of sediment during extreme storm events. This sediment is lost to the system and may lead to eventual degradation of the beach. Figure 7 shows a simplified model of theorized sediment supply, originating from the Guajataca river, transported by longshore currents and distributed by wind and waves which have and still are supplying sediment to the coastal systems around Isabela. If it is determined that there is a net loss to the system, then the current sediment supply is not sufficient to maintain any loss to the beaches from the washover effect. If the beaches are determined to be stable, then there must be enough sediments to provide nourishment to the beaches. Also to be analyzed are any

contributing factors to the shoreline such as housing development and restoration of wetlands which should have a respective net negative and positive effect to the position of the shoreline.

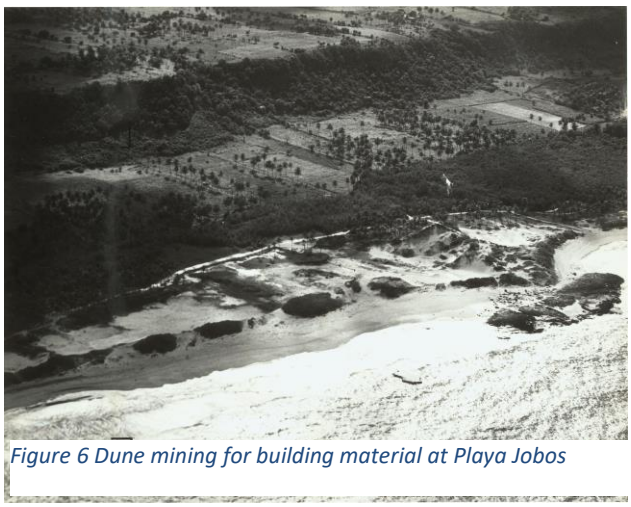


Figure 6 Dune mining for building material at Playa Jobos

Figure 5 Aftermath of dune mining at Playa Jobos

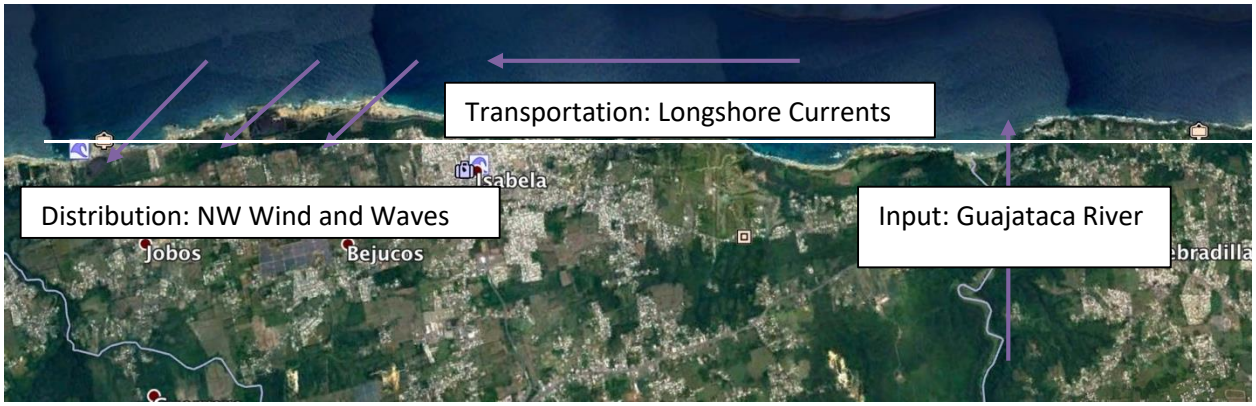


Figure 7 Overview of study area and simplified sedimentation system. Much of the sediments from the dunes and beaches is theorized to originate from inputs delivered to the coast from the north coast river transporting eroded batholith a carbonate material into the ocean. This is then transported laterally along the coast by dominant wind, wave and ocean currents and eventually deposited again to form the north coast aeolianite complexes.

METHODOLOGY

Three beaches were chosen in the Isabela area based on their accessibility and their coverage in the 1930s orthographic photo series. Playas Jobos, Montones, and Pesquera will be characterized using four sources of data representing 3 distinct time periods. The first data series is the orthographic photos from 1930 which is composed of a mosaic of georectified aerial images. This shows us the well preserved coastline before the destruction of the dunes and before large coastal property development occurred. The 1930s photos also show a time before the abandonment of sugar cane production, giving a before and after snapshot of land use. Previously highly cultivated land has been either restored to its natural state as coastal

wetlands (Figure 8), or is left fallow. The second data set is the 1 meter ESRI satellite georeferenced photo mosaics that are available freely through Arc GIS. The photos from this series was obtained on September 14th, 2009 (Figure 9). A third data set was acquired from the Sentinel 2 satellite and are images from April 8th, 2019 (Figure 10). The last data set consist of GPS points obtained on April 15th, 2019 at Playa Jobos and Montones and on April 24th at Playa Pesquera. The data was recorded on a GPS collector at 1 second intervals and later converted to an ESRI shape file. The GPS data is accurate within a few centimeter of error.

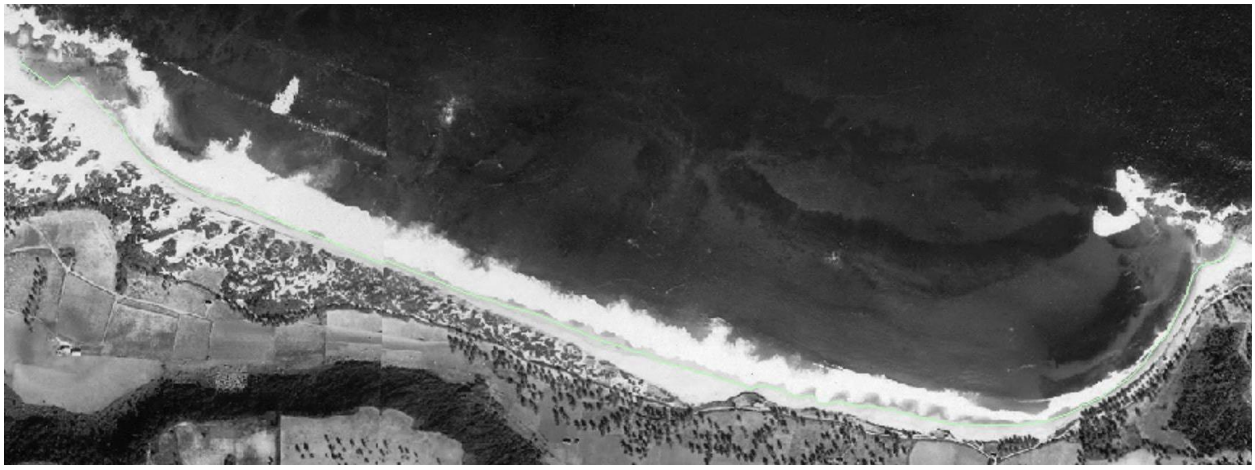


Figure 8 overview of Playa Sardinera from the 1930s ortho-rectified aerial photograph series (top) and from the same beach in figure 10 below in 2009. Notice the intact coastal dune in the west which abuts against fields which were exploited for agriculture. In the east notice that compared with the modern photo below there is no development in the east of the beach

Figure 9 modern overview of Playa Sardinera from ESRI stock aerial imagery captured in September 2009

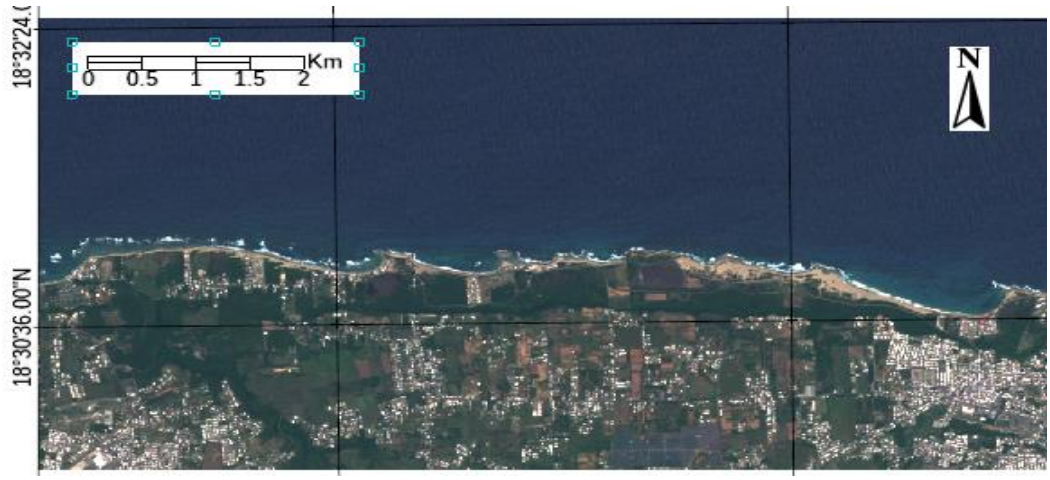


Figure 10 Overview of study area with the true color image of Sentinel 2A data

Data was processed using both ENVI and Arc GIS software. ENVI software was used to process the Sentinel 2 data and extract the coastline. Both band 8, the raw Near Infrared image (NIR), and a combination of band 8 and 4 (Red band), to calculate NDVI (NIR-Red/NIR+Red), were utilized. The image was then run through unsupervised classification: K-means & Iso-Data, to find the best method to classify the shoreline as distinct from the water. Through visual assessment it was determined that the coastline made from the NDVI, K-means classification. The final version polygon was vectorized and exported as a shapefile to be digitized in Arc GIS.

Figure 11 High tide wrack line and smooth intertidal sand Playa Jobos

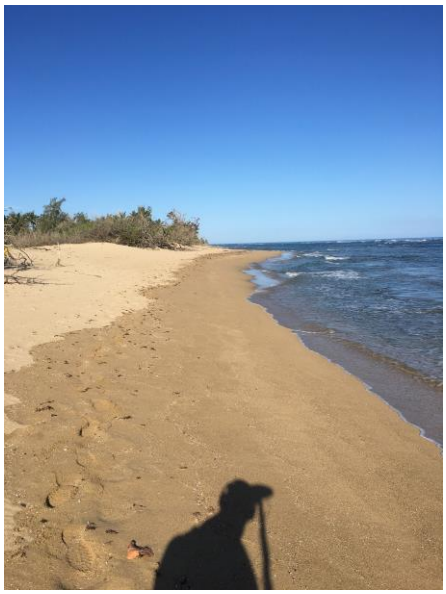


Figure 12 color reflectance variation intertidal sand Playa jobos

In order to digitize the various data sources, the high tide line was chosen as the shoreline. GPS

data was collected at low tide as there was an obvious manifestation of the high tide line along the remnants of a wrack line Figure 11) Also there was a marked difference between the color reflectance of the wet intertidal sand and dry sand above the high tide line (Figure 12). As well The intertidal sand also displayed a marked difference in its smoothness as opposed to the rough windblown textures of sand above the high tide line. Based upon field observations, digitization of the images was based on identification of the wrack line, changes in color and in texture of the sand (Figure 13).

After digitization of the images the Digital Shoreline Analysis System (DSAS) was used to calculate the total change in shoreline between the different years. DSAS is a freely available toolbox and was utilized by Thieler et. al. (1995) in the analysis of the coastline around Rincon. DSAS Shoreline Change Envelope (SCE) computes the maximum change in shoreline (Figure 14).

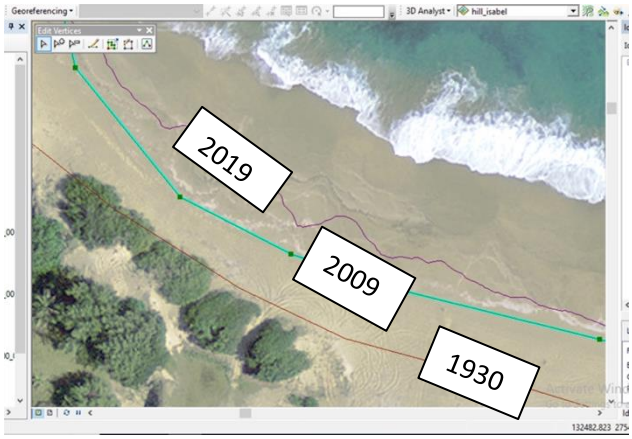


Figure 14 digitalization of Playa Montones shorelines within Arc GIS. Notice the aggradation of the shoreline from 1930 to 2019.

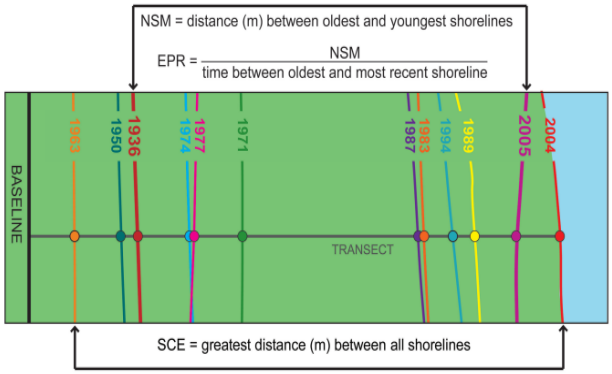


Figure 13 DSAS toolbox from the USGS. The SCE calculation measures both spatial and temporal variability within a scene (Thieler et. al. 1995).

RESULTS

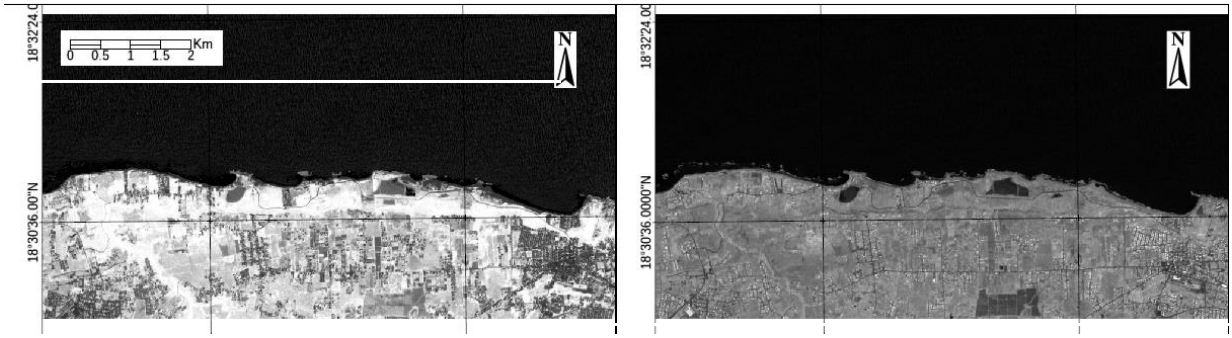


Figure 15 NDVI (left) NIR (right)

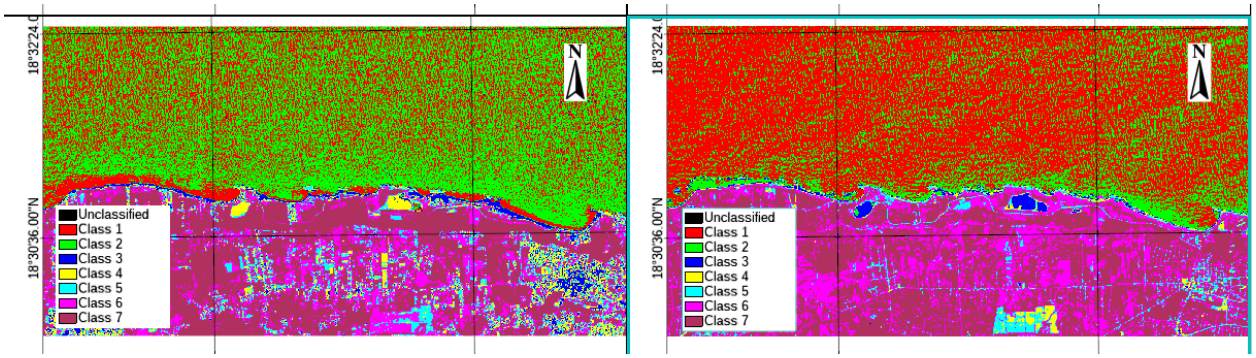


Figure 15 K-means Classification

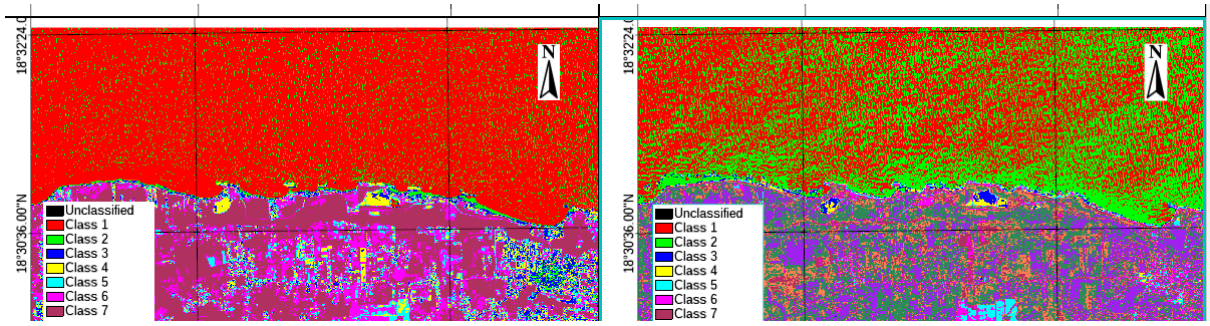
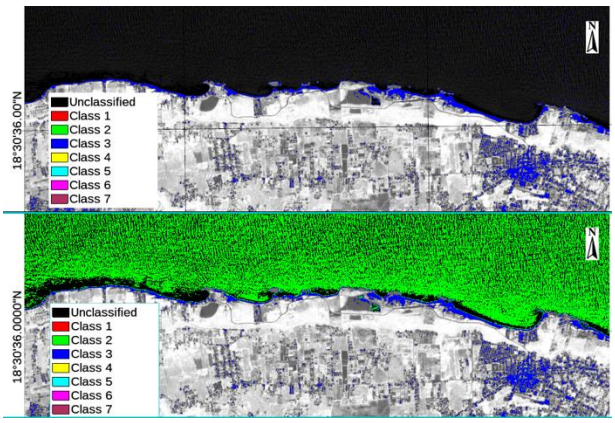


Figure17 Iso Data Classification



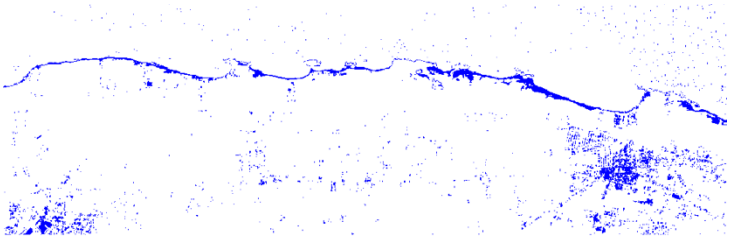


Figure 18 & 19 K-means Classification Class 3 (top left) class2 & 3 (bottom left), Class 3 extraction for Arc GIS (top).

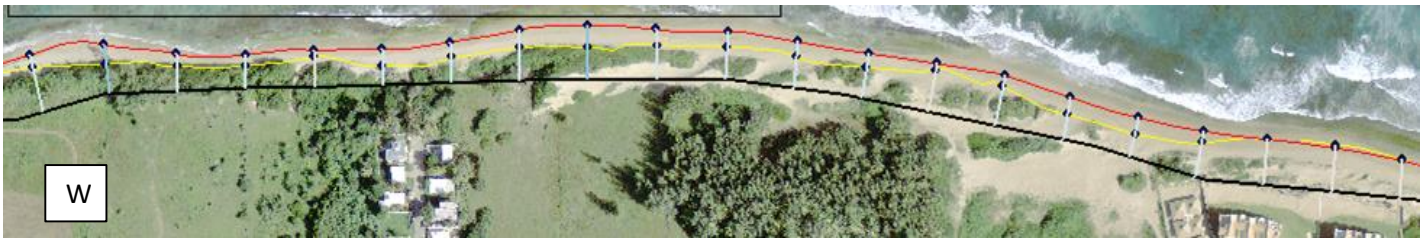


Figure 16 Playa Jobos West

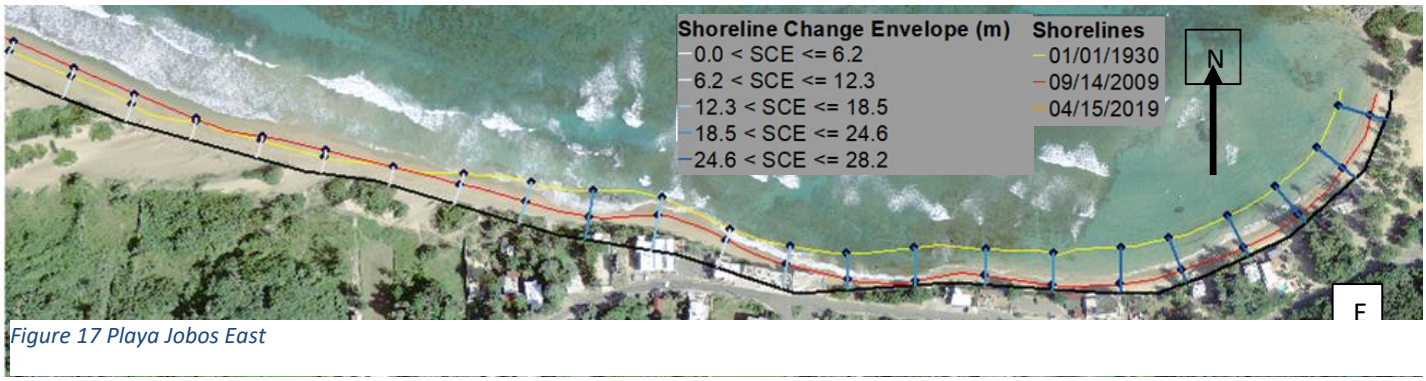


Figure 17 Playa Jobos East

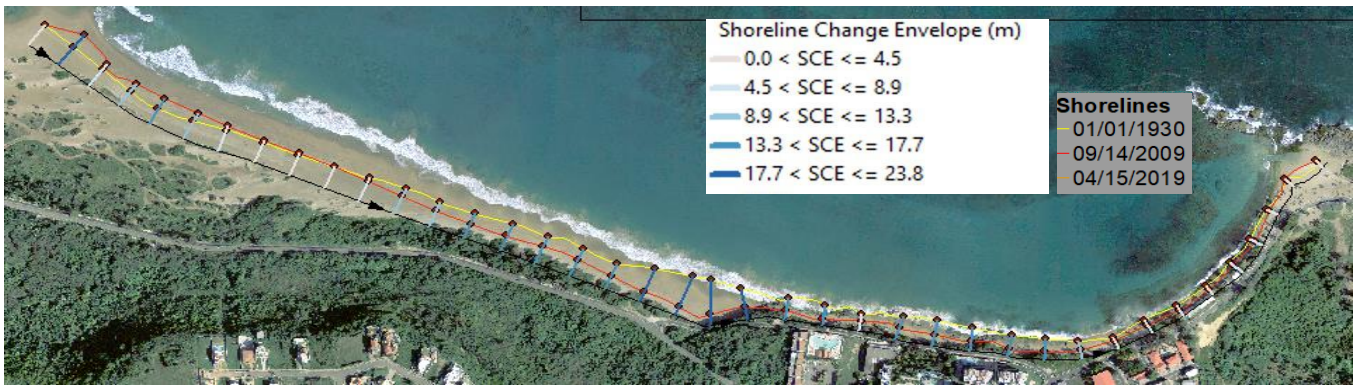


Figure 18 Playa Montones

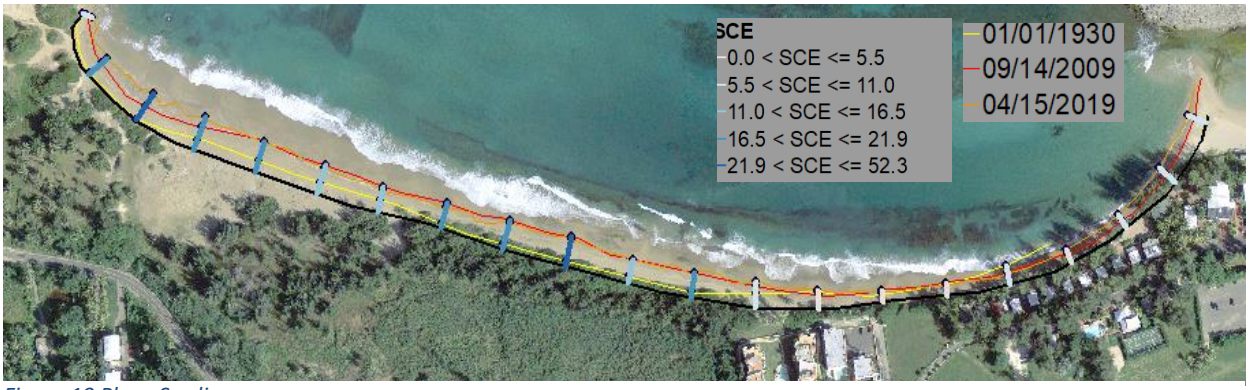


Figure 19 Playa Sardinera

DISCUSSION

ENVI was used to extract the polygon of the beach from the Sentinel 2 image of the three beaches. Inspection of the NDVI outputs and NIR using Iso-Data and K-means Classification (Figures 14-18) showed that Class 3 from the K-means Classification best fit with the modern shoreline. The Class 3 subset of the NDVI K-Means Classification was exported as a Vector Layer to be imported and digitized in Arc GIS (Figure 19). However, there was trouble with the projection file of this new image and so a comparison between the 2019 shorelines derived from Sentinel could not be compared with the 2019 GPS data. It is assumed that because of the high accuracy of the GPS data and the low resolution of the Sentinel 2 data there would be too much uncertainty from Sentinel 2 to make it very effective for this study. Average change over the 90-year span of the data sets was around 10 meters which is the resolution level of the images.

Shoreline Change Envelope outputs for the 80-90 year study window show that Playa Jobos and Montones were accretionary beaches while Playa Pesquera an erosional beach. Maximum shoreline changes on Playa Jobos and Montones was ~28 and ~24 meters, respectively. Maximum shoreline changes on Pesquera was ~52 meters. Accretion typically occurred along the western halves of the beaches while erosion occurred on the eastern beaches. The pattern of spatial variability of spatial and erosional rates relates to the density of shoreline development. The shelter of the cove-like shape of the beaches means that it is more favorable to build houses in the eastern half of the beaches. The western halves of the beach remained less developed.

Recalling Bush et. al. (1995), that construction reduces a shoreline 'natural flexibility, 'it comes as no surprise that erosion occurs primarily on eastern half of the beaches. With the installation of permanent hard structure, the shoreline cannot ebb and flow with the seasonal accumulation and depletion of sand. In Playa Pesquera where the maximum erosion of ~52 meters occurs from hard stabilization constructed to bolster the coastal road and houses has retarded the natural accumulation of sediments (Figure 23). The erosion envelopes in Sardinera is nearly double of that of the next closest erosional profile in Playa Jobos (Figure 21) which had a maximum erosion envelope of ~28 m. While hard stabilizations are good at temporarily preserving coastal structures, they are notorious for undermining beach sediments and was cited as a major cause of shoreline depletion in the Rincon area (Thieler et. al., 1995).

Figure 20 Close up of groin at Playa Pescara and the maximum erosion from study area - 52.3 meters.

Changes in Land use, while having a negative impact on shorelines due to coastal development reinforcements, can have a positive impact where coastal agronomy practices are abandoned. The 1930s photos captured the maximum extent of agricultural land use in Puerto Rico (Figure 8). Farms were increasingly abandoned in the 1940s as Puerto Rico's economy shifted from agrarian to industrial. Subsequently this fallow land returned to its more natural state as can be verified in the 2009 Aerial Photos (Figure 9). Figure 25 & 26 shows the western extent of Playa Montones. Notice that a reduction in Dune coverage does not result in a reduction of shoreline extent. Rather, the extent of the shoreline could be attributable to the abandonment of agriculture and amounts to answering the call of Pinkley et.al. (2007) who called for a retreat from the coastline in order to preserve the coastline which requires a wide buffer zones. Similarly, in the western half of Playa Jobos (Figure 20) where a general retreat from the shoreline has occurred from the 1930s to 2009 with respect to agriculture, even though the dunes have been destroyed there has been accretion of land.

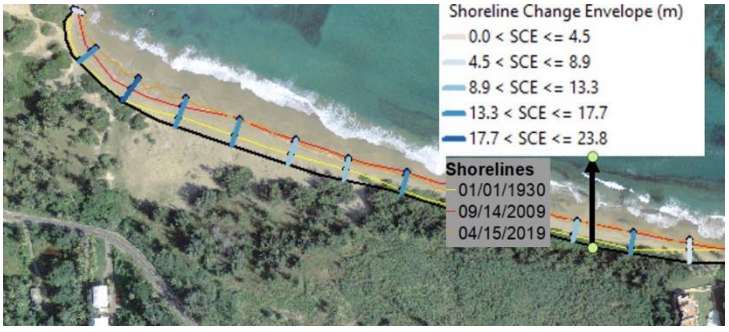


Figure 21 Playa Montones land use change: 1930s agriculture (left) and return to natural vegetation (top) results in accretion of shoreline

While data trends data show that there is accretion of sediments in the west and erosion in the east along each beach, the actual range of the Change Envelope could be higher or lower based upon uncertainty within the data. While every effort to digitize the aerial photos accurately was made, the resolution of the 1930s images made it difficult to do so with great precision. Another source of error is inconsistent of tide heights between sampling dates. Between the various images used and dates of GPS data acquisition it is unknown if these were done at the similar tide heights. Both of these variations are relatively minor. While there is likely a couple meters of variation in digitizing the images and there is only ever about 1 meter of tide flux. The DSAS function has as a default parameter 4-meter uncertainty factor that actually encapsulates these uncertainties.

It is also unknown whether or not these fluxes are actually just seasonal variability. It would require a very extensive survey created some inconsistent. There should be a much larger data set collected throughout the year as was done in the USGS survey of Rincon to cancel any seasonal noise. It is recommended to use higher resolution images obtained by Ikonos that can be rectified to a 1-meter resolution with the Panchromatic correction. An automated process can be utilized to build a robust data set that will lower overall noise from seasonal signals.

CONCLUSION

Even though the dunes have been reduced in size and there is evidence of washover which can locally produce net losses to the coastal sediment supply, there is still a net surplus of sediment into the system as is evidenced by accretion of sediment in the western portions of the beach. It would seem that land use is actually driving shoreline change. With ample sediment supply the abandonment of agriculture on the coastline post-WW2 has largely returned the natural resiliency of the coastline. Though, where urban development has persisted, there has been a net loss to the shoreline. Further investigation would have to be done on the beach sand to understand provenance. Interviewing local fisherman revealed that offshore reefs have been dead for the last 50 years. If it is determined that a significant portion of the sediment supply is sourced from these carbonates, a reduction in the coastline could yet occur as the remaining reefs are eventually reduced. The reduction in the barrier reefs will also contribute in the long term to more storm energy which could have an erosional effect of the beach. It is the suggested that a retreat from the shoreline is immediately commenced to create a buffer zone so that the coastline can adjust in the future to fluctuations caused by rising seas and increased storm surge.

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