Land Use and Land Management during the Past Century Determine Mangrove Dynamics in Northwestern Puerto Rico: the Case of the Maracayo Mangrove

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Abstract: Political and economic decisions have determined throughout the history of Puerto Rico land use for agriculture, livestock and urban sprawl. Knowing this, this study is imperative to understand how these changes caused by the various uses and management affected adjoining wetlands. It is hypothesized that these changes affected the hydrology of the area, resulting in increased salinity, providing the right niche for the development of current mangrove. The resources used were aerial photographs, oral history, a report done in 1979 by the Department of Natural and Environmental Resources of the Government of Puerto Rico and analyses of salinity, pH and conductivity of soils in three different sites. The conclusion of this study was that the wetland underwent changes in ecosystem composition by ambitious elimination of sand dunes due to hydrological changes and marine effects. The oral history confirms the presence of springs in the past and present. Salinity intrusion was documented in those springs in the 1979 report due to land use change and elimination of sand dunes, changing the habitat, therefore allowing a mangrove community to be established. The continuity of ecophysiological and hydrogeological studies of the area will allow for a predictive understanding of how the mangrove wetland will continue developing.

Key words: GIS, mangrove, wetland, land use, dynamics.

1. Introduction

Coastal wetlands ecosystems play a crucial role with the ecosystem services, they provide: (a) storage and export of carbon; (b) nursery for important fish in the fishing industry; (c) coastal protection from tsunami sand cyclones; (d) “construction of soil” or creation of land as it offers great ability to trap sediment; and (e) its influence on carbon sequestration product of peat formation [1].

Of the large number of coastal wetland ecosystems that thrive in the tropics, one of them is mangrove forests. Unlike any other forest, mangrove trees grow

in waters with marine influence, whether in tropical coastlines, lagoons, bays, riparian strips or small coastal islands [2]. The mangrove ecosystem can have more than 80 species of halophytes, salt-tolerant plants [3]. Unfortunately, mangroves worldwide have suffered great decline being felled for timber, aquaculture practices, urban construction and coastal landfill. During the last quarter century, mangrove losses quantified from 35 to 86% [4]. Along with the elimination of forested area, richness in mangrove species [4] is being diminished. The overall spatial distribution of mangroves for 2,000 shows the extent of these ecosystems in the globe [5]. Although this distribution was plotted using photographs of 16 years, it is a good guide for standard coverage of mangroves in the world. From this worldwide distribution, only

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6.9% are located in protected areas [5]. Given this urgency, there are a lot of mangrove species that are threatened and critically endangered species around the world [6]. In just the next 100 years, the area comprising mangrove forests can be so degraded and so small that they might be considered missing [4].

Alongside the area's physicochemical factors, the geomorphology comprising the ecosystem determines the structure thereof. There are a variety of ways of classifying mangrove communities by structure [7]. Among all the possible classifications, Miller, G. L. and Lugo, A. E. [2] classified Caribbean mangroves as:

- Coastal mangroves: characterized by growing in floodplains with lateral water flows and low salt concentrations;
- Mangrove basin: grow in depressions where waterflows are slow and the vertical flow of water prevails lateral flow;
- Marginal mangroves: they grow on the edge of the sea or other bodies of water that are exposed to fluctuations of vertical water and wave fronts;
- Mangrove islands: sea occur outside on small islands where the tide flows over the islands;
- Dwarf red mangrove: red dwarf are mangrove forests growing on peat and shrunk in size by being in exposed to extreme conditions such as hypersalinity and nutritional limitation [8].

The dominant species of mangroves in the Caribbean and specifically in Puerto Rico are the red mangrove (*Rhizophora mangle* L.), black mangrove (*Avicennia germinans* (L.) L.), white mangrove (*Laguncularia racemosa* (L.) C. F. Gaertn) and button mangrove (*Conocarpus erectus*) [2]. The tolerance of these four species to various factors such as the salinity of interstitial water, oxygen supply to the roots and nutrient availability determines the distribution of these in the area comprising the ecosystem [9].

Mangrove communities are located according to factors such as: wave intensity, precipitation and freshwater runoff. One of the determinants of the

structure of the mangrove is wave energy [10]. High-energy waves are associated with large coastal erosion and destruction of other geomorphological aspects that hinder the development of the mangrove. Instead, low-energy waves provide the conditions for the rapid growth, aging and death of the mangroves by the accumulation of high concentrations of salts [10].

The northern coast of the island has high energy waves, fluctuations in salinity due to fresh water runoff and a higher annual precipitation compared to the southern coast [10]. Notably, the north coast of the island is dominated by a karst landscape, influencing the hydrology of the area by a number of underground channels that flow and burst forth as springs [11]. Mangroves on the north coast have greater structural complexity, higher growth rate and leaf fall, compared to those of the south coast [2].

In addition to the mangroves, sand dune systems used to proliferate on the northern coast of Puerto Rico, which are transported and deposited by high wave and wind energy [2]. Sand dune shave are as that can sustain vegetation when stabilized, if sand deposition does not exceed the ability of plant growth [2]. In the present, few sand dune complexes can be found on the island. Of the few sand dunes, the highest are found in the municipality of Isabela, which can reach up to 15 meters high. Sand dunes are an essential barrier to the strong sea waves and a source to replenish beach erosion [2]. During the last century, large extractions of sand dunes occurred on the northern coast of the island for construction and other activities. These extractions gave way to collapse and removal of protection for future hurricanes and floods [12].

Coastal wetlands in the Caribbean, and specifically in Puerto Rico, have been altered and modified since the indigenous colonization from 5 to 7,000 years ago to the present [13]. They have been extensively modified since the colonial era as a result of changes inland use during the Spanish colonization from 1493-1898, subsequent colonization of the United

States after the Spanish-American war in 1898 which implemented hydrological changes for agriculture, and further industrial and residential development during the 20th century continued to alter these ecosystems. The zonation of plants was modified due to the drying of wetlands by drainage, excessive felling of trees, removal of coastal dunes and alteration of the hydrology of the sites as a product of agriculture and human settlements (town and neighborhoods) [14]. During the last two centuries in Puerto Rico, mangrove areas have been transformed in order to be used for urban development [14]. With a dramatic rise in the human population, changes in the economic base on the island, land use and extensive coastal development, the area covered by mangroves was significantly reduced [14]. Changes in land use in the last two centuries are separated by an agricultural and industrial era. During the agricultural era (1800-1950), there was a massive decline in mangrove cover. On the other hand, the change to the industrial era (1950-present) brought about a brief natural recovery.

With the establishment of legal protection in 1972, the mangrove extension, although fragmented, has continued [14].

Wetlands and coastal dunes are normally associated, so, any changes affect this dynamic ecosystem. The changes in land use and management of coastal systems in Puerto Rico had a decisive effect on their dynamics. Therefore, it is important to determine how these changes have affected the composition of wetlands according to past and present history of their environment.

The study area is located in the northern side of the island in the municipality of Camuy, northwest to the Barrio Pueblo, approximately one kilometer to the west of the mouth of the Rio Camuy and approximately 135 meters from the sea (Fig. 1). The Rio Camuy basin receives an average of 77 inches of rain per year (1,956 mm) and has a humid tropical climate. The study area falls within the calcareous karst region of the northern coast of the island [15]. This mangrove wetland is known by various names,

Fig. 1 Aerial photograph from 2015 taken from Google Earth of the town center of Camuy, Puerto Rico (red rectangle to the right) and the neighborhood of Membrillo, Camuy, Puerto Rico (red rectangle to the left).

such as the Mangrove of Camuy, Maracayo Mangrove, Mangrove of Peñón Brusi and Finca Nolla. The mangrove wetland comprises the grounds of the Finca Nolla, a previously privately owned land acquired in 2014 by the Department of Natural and Environmental Resources of the Commonwealth of Puerto Rico, which comprises 0.45 square kilometers with borders in the north with the maritime zone [16].

At present, the study area is home to a diversity of species in the mangrove forests and the sandy coast. This mangrove wetland is characterized by the presence of natural springs. In the area, the four species of mangroves are observed: red mangrove (*Rhizophora mangle* L.), black mangrove (*Avicennia germinans* (L.) L.), white mangrove (*Laguncularia racemosa* (L.)) and button mangrove (*Conocarpus erectus* L.), along with other non-halophyte species, such as Lengua de Suegra (*Sansevieria trifasciata Laurentii*), Almendrón (*Terminalia catappa* L.) and Emajaguilla (*Thespesia populnea* (L.) Sol. ex Corrêa).

As early as 1889, what is today referred to as the Mangrove of Camuy, appears as a part of a more extensive on the Spanish military map entitled *Itinerario de Hatillo a Quebradillas* [17]. Fig. 2 shows this military map found in reference with an image taken from Google Earth, presenting the town of Camuy and the adjacent Mangrove of Camuy. The inventory report of mangroves in Puerto Rico published in 1979 mentions this mangrove as the Peñón Brusi Mangrove [18]. It presents a brief description of the mangrove and structural data analysis. Interstitial salinity, DBH (Diameter at Breast Height), canopy height, distribution of species of the area and other data were also assessed. This document was used to compare the conditions of this mangrove wetland in the past with the new data obtained and analyzed for this study.

The land comprising the study area was not exempt from the changes inland use that suffered the vast majority of Caribbean islands' landscapes due to

socioeconomic changes [14]. Agricultural and livestock demand, urban sprawl and other anthropogenic activities on the island have impacted the mangroves on the island for over 200 years [14]. With the abandonment of most of the coastal agricultural land in the last 60 years in Puerto Rico, an increased recovery in the wooded area across the island has been observed [19].

The original wetland shown in the 1889 map has undergone extensive change, as product of the changes in the use and management of the land over time, as evidenced by various historical aerial photographs. The objective of this research is to reconstruct the history of the land use and management of the study area and how these changes have impacted the conditions of the area comprising the current mangrove wetland. The impact of the change in the use and management of this area, over time, affected the hydrology of the area developing the appropriate conditions for the development of the current mangrove forest, after the abandonment of farming practices. This paper proposes to determine how the change of use of the past and present land affects the presence and development of a mangrove wetland area in Camuy, where historical data indicates original possible palustrine conditions. The hypothesis is that temporal and spatial dynamics of the Mangrove of Camuy was determined by the change in hydrology, product of the land use and management of maritime-terrestrial land for agricultural use and the extraction of the sand dunes.

2. Methods

In order to quantify the changes brought about in the area, these documents were used: (a) the Spanish military map of 1889 (Figs. 3 and 4); (b) the mangrove inventory report of 1979; and (c) aerial and satellite photographs from 1930 to 2015. The ArcGIS program (Geographic Information System Computer Program) [20] was used to carry out the spatial analysis of the study area. The aerial photographs

Fig. 2 This figure shows the military map of 1889 (above) entitled *Itinerario de Hatillo a Quebradillas*, showing sorting area to the town of Camuy in red. The map scale is 1: 20,000 with contour lines with equidistance of 20 meters. At the bottom, shows a satellite photograph of 2015 provided by Google Earth presenting the same area as the military map.

Fig. 3 Sketch of the area of the town of Camuy in 1889.

Fig. 4 The military map of 1889 showing the study area enclosed in red. The yellow dots show the soil sampling sites.

Fig. 5 Photograph of the area in 1930 showing the impact of agriculture in the study area which is marked in red. The yellow dots show the soil sampling sites.

utilized were taken in: 1930 (Fig. 5), 1936 (Fig. 6), 1951 (Fig. 7), 1963 (Fig. 8), 1977 (Fig. 9), 1987 (Fig. 10), 1997 (Fig. 11), 2010 (Fig. 12) and a satellite photograph of 2015 from Google Earth (Fig. 13).

The military map corresponds to the topographic itineraries made by the Topographical Commission by the Spanish colonial government in 1889, belonging to Cartographic File and Geographical Survey of the Geographic Center of the Army who managed to digitalize the documents [17]. The photographs, as well as the military map, were georeferenced using the tool in the ArcGIS program, where the wetland area and sand dunes area are present. In each photograph, the area that consistent of wetland and sand dunes were calculated. They were taken from a minimum of 4 to 10 benchmarks to achieve georeferencing in the program and reduce the margin of error represented in the RMS (Root Mean Square) Total: a lower RMS, the higher average precision in digital representation of photography [21]. Differences in the temporality gave difficulty finding reliable benchmarks. The biggest challenge was the military map by its scale

and resolution. The scale appears to be feasible in some parts of the map like the main roads and the coast but not to the scale used in representing the town of Camuy. For this reason, the georeferencing was based on the rocky headlands of the coast.

After georeferencing all the photographs and the military map, a comparison to verify visible changes was done with each photo and the photo of the nearest previous year. A series of interviews were made to inhabitants who have lived for more than 30 years next to the wetland in order to document the oral history of the place. A questionnaire was presented to the interviewed (Appendix 1), which briefly served to document the knowledge and oral histories of people who have a connection to the Mangrove of Camuy. As part of the requirement for studies concerning humans, the UPRRP (University of Puerto Rico, Río Piedras Campus) has as a policy to provide training and a certificate in order to continue forward with these studies. In The Research of the UPRRP, CIPSHI (The Institutional Committee for The Protection of Human Beings) certification for studies with human subjects

Fig. 6 Photograph of the area in 1936 showing the study area in red and the soil sampling sites in yellow.

Fig. 7 Photograph of the area in 1951 showing the study area in red and the soil sampling sites in yellow.

Fig. 8 Photograph of the area in 1963 showing the study area in red and the soil sampling sites in yellow.

Fig. 9 Photograph of the area in 1977 showing the study area in red and the soil sampling sites in yellow.

Fig. 10 Photograph of the area in 1987 showing the study area in red and the soil sampling sites in yellow.

Fig. 11 Photograph of the area in 1997 showing the study area in red and the soil sampling sites in yellow.

Fig. 12 Photograph of the area in 2010 showing the study area in red and the soil sampling sites in yellow.

Fig. 13 Photograph of the area in 2015 taken from Google Earth showing the study area in red and the soil sampling sites in yellow.

was obtained. Community leaders of the Calle Abajo district were contacted in order to contact six people who had greater knowledge of the area at its discretion. These six people were given the questionnaire whose content refers to the history of the use and management of mangrove land in the past, among them: its use as a dump area and massive extraction of sand. In addition to the questionnaire, they were asked to identify where the known freshwater springs were in the wetland using an aerial photograph of the area.

To compare the physico-chemical data presented in 1979 [14] in order to determine whether the conditions in the wetland remained similar, two soil samples were taken from the surface to 10 cm deep in three points in Site I and II, and one sample in IB. The samples were analyzed for salinity, pH, conductivity, organic carbon and mineral content (%). Two laboratory replicates from each sampling site were taken. The first replicate was used to determine salinity and conductivity (2 g soil: 10 ml deionized water). The samples were thoroughly mixed in a shaker, stood still for 30 minutes and later centrifuged for 2 minutes at 1,000 rpm, and were left to settle for about 5 minutes. The supernatant was used for salinity analysis using an Atago refractometer salinity (‰), pH with an Orion 420A and conductivity using a Hanna Instruments HI993310 conductivity meter ($\mu\text{S}/\text{cm}$). The second set of replicates was analyzed for percentage (%) total organic carbon and mineral content using loss on ignition methodology [22]. As the samples were highly organic (peat) they were treated as organic samples, fresh weight was determined, dried in a Shell Lab forced air oven at 60 °C for twenty-four hours and weighed again for % moisture determination. The dried samples were homogenized and two laboratory replicates 1g per sample were placed in crucibles and placed in a Thermolyne 30400 Muffle Furnace at 550 °C for 24 hours. After 24 hours the crucibles were taken out and placed in a desiccator to prevent moisture weight gain,

and re-weighed after cooling. The data was analyzed using JMP®, Version 10, SAS Institute Inc.

3. Results and Discussion

3.1 Aerial Photographs in ArcGIS

A series of diverse results arose from this study. After georeferencing all the images found of the study area, the study area was plotted in the photograph of 1930 and then compared with each image found to observe the change that the area has suffered. Additional comparison of the sand dune area and wetland area to assess its changes were done with all pictures and the military map in relation to the 1930 picture. These can be seen in Figs. 14-23. Also, three transparencies between two photos each were made to show the change in various years. The first (Fig. 24) shows the photograph of 1930 and 1977 putting one on the top of the other with transparency to see the change. The same was done with photographs 1977 and 2010. The transparency is between photography of 1977 and 2010 (Fig. 25), where forest recovery was seen towards the sand dune area. Moreover, calculations of the wetland area were done in all aerial pictures and were summarized in Figs. 26-28. Furthermore, the interviews provided a social insight of the study area, illustrated in Fig. 29. Last, statistical analysis of different factors taken from the soil samples collected from the three sites are summarized in Figs. 30-34, helping with argumentation to support the discussion.

The comparisons of all pictures after georeferencing were made at a scale of 1: 6,000. On the military map of 1889 (Fig. 4), the wetland spread west and east at a great distance demarcated on the map with a red polygon and into this with symbols classified as a wetland area. On the military map of 1889, a wetland ecosystem is classified behind a large dune system ranging from the Río Camuy's river mouth in the east to the Membrillo ravine in the west, ending behind the Peñón de Brusi, as specified by the map is described.

By 1889, there was no presence of the drainage channel that is seen in the 1930 photograph present on the south side and west side of the study area. This channel continues to function and its mouth opens and closes according to the amount of water in the wetland that eventually drains into the sea. This channel established a hydrological change that continues to the present. A reduction in the area occupied by the wetland is observed. It should also be said that in the military map of 1889 wetland vegetation type was not identified or described, it was simply classified as a wetland on the map. For this reason, it is unknown whether it was a palustrine or estuarine wetland. In addition, there needs to be consideration that all maps have a margin of error. This way, an assumption that this area on the map has been modified on a large scale can be made. Comparing the map with the photograph of 1930 (Fig. 5), there is a drastic change. In the photograph of 1930 (Fig. 5), a dense timberline area can be seen on the site where springs flourish while the rest of the area to the right has grooves in the land, like the contour-furrow method used in agricultural practices. It can only be assumed that these lands were planted with sugar cane as various sugar mills existed nearby like the Central Camuy, Central Alianza and Central Soller, indicating the strong sugarcane planting in the area. In addition, approximately one kilometer from the current wetland is the ruins of the Central Riollano [23]. Channels and trenches were typical farming techniques used to drain excess water from the ground and prepare the land for planting. Such structures initially played the lead role in the physical change of the wetland. In the photograph of 1930 (Fig. 15), a large vegetated sand dune system is seen with steep drop into the sea as well as a wooded area, where the springs flourish. Please note that for 1923 the Central Alliance had closed its operations [24]. By the photograph of 1936 (Fig. 6), 13 years later after the closing of the Central Alianza, an increase in the forested area can be observed from the previously demarcated agricultural

area in 1930. This may have occurred by the abandonment of hydrological control of the area, in turn favoring a high soil saturation condition. The sand dune and dune vegetation seem intact. Moreover, in the Property Registry for the Camuy area, located in Arecibo, a document concerning this land called Finca Nolla was found of the estate comprising mangrove land (land registry number: 010-000-003-01). This farm is a union of six farms. No further information on the six farms was found, since they are documents from the early nineteenth century and are not available to the public.

The photograph of 1951 (Fig. 7) shows that the area had been abandoned for agricultural use and the wetland begins to recover east of the area by the marked increase in the timberline area. The sand dunes maintain their structure as seen from the photograph of 1930 (Fig. 15). For 1963 photograph (Fig. 8), homogeneity is seen by the roughness in the marked arboreal area. The trenches witnessed in the previous photos are not visible except those in the southern center of the 1963 photograph (Fig. 8). The wetland appears to be in a fast-successional recovery process. It can be observed how the mangrove has colonized the land to the right of the study area. In addition, it looks like little by little the trenches or channels made for agriculture begin to disappear. In the 1977 photograph (Fig. 9), a decrease of the forest directly adjacent to the sand dunes on the beach is observed. Also, the grooves or channels disappear completely. It seems the flow of water from the wetland has been restored. A significant decrease in the sand dune vegetation is seen in Fig. 9. This decrease may have happened due to the massive extraction of sand that this area experienced, leaving part of the wetland exposed to strong winds and wave energy. This is consistent with the extraction of sand that is known to have been carried out in the 60s and 70s on the island [25]. Even with efforts to restore dunes in the area, this will not reverse the wetland to its condition in the past, because the terrestrial marine interaction is much

Fig. 14 Military map of 1889. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil sample sites.

Fig. 15 Photograph from 1930. In red, the study area is depicted. In orange, the sand dune area is enclosed. The three yellow points indicate the soil sample sites.

Fig. 16 Photograph of 1936. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil simple sites.

Fig. 17 Photograph of 1950. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil simple sites.

Fig. 18 Photograph from 1963. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil sample sites.

Fig. 19 Photograph of 1977. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil sample sites.

Fig. 20 Photograph of 1987. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil simple sites.

Fig. 21 Photograph of 1997. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil simple sites.

Fig. 22 Photograph of 2010. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil sample sites.

Fig. 23 Satellite photograph of 2015 taken from Google Earth. In red, the study area is depicted. In orange, the sand dune area from 1930 is enclosed. The three yellow points indicate the soil sample sites.

Fig. 24 Aerial photograph transparency (34%) between 1930 and 1977 shown in the study area red and yellow dots sampling points.

Fig. 25 Aerial photograph transparency (45%) between 1977 and 2010. The study area is shown in red and the sampling sites in yellow dots.

higher, which will increase with sea level rise, keeping the geo-hydrological conditions for maintaining a mangrove ecosystem.

Looking at the photograph of 1987 (Fig. 20), there is almost complete disappearance of the large sand dune system that was in the area as well as the dune vegetation; the glare from the sun beating on the waves leaves the photo with poor quality. The wetland appears to have changed in this time frame of only 10 years, likely as a product of probable hydrological stress from very dry seasons experienced from 1977 to 1988, as the MEI (Multivariate ENSO (El Niño Southern Oscillation) Index) indicates. [26] (Fig. 34). In Fig. 14, by 1997 there is an increase in vegetation towards the sand dune area's southeastern side. The photograph of 2010 (Fig. 22) is the most current one. This photograph presents a slight increase in the sand dune vegetation and coastal erosion.

In addition, three transparencies between two photos each were made to show the change in various years. The first (Fig. 24) shows the photograph of 1930 and 1977 putting one on the top of the other with transparency to see the change. The same was done with photographs 1977 and 2010. The transparency is between photography of 1977 and 2010 (Fig. 25), where forest recovery was seen towards the sand dune area.

Moreover, Table 1 summarized the wetland areas in addition with the area of the sand dunes of each photograph, the percentage of loss or gain of area of

each photograph in reference to the previous year of the same and with reference to military map of 1889. As shown in Fig. 4, the wetland lost significant area in 1930. Then it recovered area in 1963 and declined rapidly due to the loss of the sand dunes in 1977. It was not until 1997 that there begins to be an increase in the area occupied by vegetation in the sand dunes and the wetland area itself. It has to be noted that, although the wetland area has increased in the later years, species composition might have changed as mangroves now occupy areas that were formerly lacustrine or marshland in the 1899 figure.

In short, the decrease in sand dune area is evident. Its decline is witnessed since the photograph of 1977 (Fig. 19). There was a large reduction in the sand dunes on all pictures compared to the military map of 1889 (Fig. 14). The map shows that these dunes have a height of about 20 meters in the sand dunes in the west and approximately 40 meters in the sand dunes in the east. The contour lines of the map of 1889 have an equidistance of 20 meters.

3.2 Interviews

Six people were interviewed after being referred by the community leader of the Calle Abajo sector. These 6 people have lived all their life in the Calle Abajo sector of the Barrio Pueblo and are 60 years old or more. All respondents indicated that within the mangrove there are three springs, each named by the

Table 1 Wetland area of the years provided in the aerial and satellite photographs and military map.

Year of the photograph	Wetland and sand dune area (km ²)	% of loss or gain of area of each photograph in reference with the military map of 1889	% of loss or gain of area of each photograph in reference with the photograph of the previous year
1889 (military map)	0.60	-	-
1930	0.13	-77.54	-77.54
1936	0.18	-69.57	35.45
1951	0.22	-63.52	62.37
1963	0.23	-61.56	5.37
1977	0.16	-73.10	-30.00
1987	0.13	-78.46	-19.92
1997	0.16	-73.07	24.98
2010	0.20	-65.98	26.35
2015	0.22	-63.82	6.345

Fig. 26 Graph showing the change in the area of the wetland seen in the military map in reference to the aerial and satellite photographs throughout time.

Fig. 27 Graph showing the percentage of loss or gain in the area of the wetland the aerial and satellite photographs in reference to the military map of 1889.

Fig. 28 Graph showing the percentage of loss or gain in the area of the wetland the aerial and satellite photographs in reference to the photograph of the previous year.

Fig. 29 A 2015 photograph taken from Google Earth showing in yellow the soil sampling sites and in black circles the springs and their name given by the respondents.

nearby inhabitants of this area through the years: the Ojo Sáballo, Ojo Azul and Ojo Guareto (Fig. 29). In addition, all respondents confirmed the large drop in the sand dunes from the 60s, the presence of a landfill, a slaughterhouse for farm animals and a small suburb located on top of the sand dunes in the past. They did not indicate witnessing a sugarcane plantation. The soil sampling site Site I and IB fall within the area where the respondents called the Ojo Sáballo. Site II falls within the spring named Ojo Azul by respondents. In the Site II, area covered in broken glass was found, confirming the present-day mangrove area was used as landfill. Mangroves here are found in a recent stage of development based on their DBH and height. In addition, 4 of the 6 respondents mentioned the use of mangroves for fishing and a source of fresh water.

3.3 Chemical Characterization of the Study Area—Present

Soil samples were taken in each of the three sampling points in the wetland on July 13, 2015 during low tide

(Fig. 13). The points were chosen based on the presence of two springs and flooded areas. Salinity, conductivity, pH, percentage of organic matter and mineral content of the soil of these areas were measured from the surface to a depth of 10 cm. The moisture content of the samples was also calculated. It was expected to observe high salinity measurements during low tide, as the wetland was quite dry due to a lack of precipitation during the week previous when the samples were taken. Statistical analyzes are summarized in Figs. 30-33. The percentage of organic carbon can provide information on how long an area has been colonized by vegetation.

The percentage of mineral content, the remainder of combustion to remove organic carbon from the samples, shows the influence of the geology of the area and, in this case, if this wetland has marine influence. Salinity is indicative of concentrations of salts by seawater intrusion and evapotranspiration. The instrument used to measure it was the refractometer which measures primarily sodium

chloride. The conductivity indicates the ability of a substrate to pass electric current, which relates to all amounts of salts and ions.

Organic carbon values were obtained in the three sampling sites (Fig. 32). They show a tendency to increase from east to west. Site I has less organic carbon content, followed by Site IB and Site II, with the highest amount of organic carbon. In conclusion

with this data, Site I has the greatest tidal influence from the opening and closing of a small channel that drains the wetland to the sea. In the same way, Site II seems to have shallow tidal influence and stores higher carbon content without it being washed away. There is a significant relationship between the location of the sample sites and organic carbon content ($\chi^2 = 6,000$, $df = 2$, $p \leq 0.0498$). These organic carbon

Fig. 30 Regression model of two variables, conductivity and salinity. Also, shown in the figure are all the statistical analyses summarized.

Fig. 31 Linear regression model between two variables, percent mineral and conductivity. Shown summarized all statistical analyzes.

Fig. 32 Boxplot presenting the percentage values of organic carbon per sampling site. A summary of other statistical parameters for this variable is also shown.

Fig. 33 Boxplot representing the percentage values of ore per sampling site. A summary of other statistical parameters for this variable is also shown.

values indicate that the mangrove has grown from west to east, since a large amount of organic carbon is indicative of longer vegetation presence. With an inversely proportional relationship to the values of organic carbon, mineral content decreases in the sampling sites from east to west (Fig. 33). Site I has a greater influence on the sands of the beach by the channel that drains into the sea. Therefore, Site IB and Site II contain less mineral content. This indicates that the organic carbon is stored in these sites, having less impact from the surface to a depth of 10 cm with the sea and the sand dunes. As with the results for organic carbon content, it is accepted that there is a relationship between the location of the sample sites and mineral content ($\chi^2 = 6,000$, $df = 2$, $p \leq 0.0498$). The grain

size of the soil has great influence on water retention and permeability as well as other characteristics that might determine the behavior of water flow. The ratio between the sizes of grains in the samples was not done but their characteristics are documented. The grain size of the soil and the position where sampling was taken are related. Site I has a greater influence from the sand thus having sand in the sample, while the IB Site and Site II have more influence of vegetation; no sand was visible and very dark soil.

All salinity values obtained show very low concentrations of salts in the water, being between 0 to 3 ppt. With values ranging between 0 and 3 ppt, the superficial water wetland is brackish in nature. The results show differences with the 1979 report data for

superficial water salinity, being 14‰ for this time. This can be attributed to high salinity by evapotranspiration in time of drought which was exhibited in 1979, according to the MEI [26] (Fig. 34). For this reason, measurements are expected to be higher for salinity in superficial water as documented in the report of 1979. The change in salinity values between 1979 and this study is evidence of hydrological change and influence of precipitation in the area from 1979 to the present. It should be added that between 2014 and 2015, there was a large deficit of precipitation to the east of the island by strong El Niño conditions [27]. However, the western area of the island, including the basin of Rio Camuy, did not witness any decrease in precipitation until November 2015 [28].

Because of this, the data reflect the increase in precipitation and dilution factor of fresh water in the wetland. This emphasizes that environmental parameters that dictate the behavior of the wetland fall

below normal precipitation. These measurements together with georeferenced images in ArcGIS confirm the expansion of wetland apparent after the abandonment of the land and the reduction thereof caused by possible vehicular impact and extraction of sand dunes in the area. Regarding the conductivity, all samples gave low concentrations, between 0.26 $\mu\text{S}/\text{cm}$ to 2.97 $\mu\text{S}/\text{cm}$. A relationship between conductivity and salinity (Fig. 30) was observed. The linear regression model shows validity (F value = 0.0162). Similarly, a relationship between percent mineral and conductivity was observed.

Values for pH average in all sites between 7.5 and 8.3 approximately (Table 2). The neutral to alkaline pH values (7-8) is generally indicative of the limestone geology [29]; in this case, of the karst geology of the area. The spring water in this wetland is from water running down the basin of the Rio Camuy, bringing dissolved minerals from limestone strata formations Lares and Cíbaro [30].

Fig. 34 Graph showing the MEI between 1960 to 2015. Positive values displayed (in red) are associated with El Niño events and negative values (blue) are associated with La Niña events (<http://www.esrl.noaa.gov/psd/enso/mei/>) [26].

Table 2 Parameters measure from the soils samples (0-10 cm depth) in all three sites.

	Site I	Site IB	Site II
pH	7.88	7.56	8.13
Salinity (‰)	2.75	0	1.5
Conductivity (mS/cm)	2.41	0.27	1.13
Moisture Content (%)	66.15	91.35	63.79
Organic Matter (%)	40.26	83.55	86.83
Mineral Content (%)	59.72	16.45	13.18

The moisture content of the samples indicates if the ground is saturated with water, indicating whether it is a flood-prone area. Soils with high water content are indicative of soil or water flooded soils [31]. If flooded, this indicates the water table or soil saturation level. The results show differences in the percent moisture. At 10 cm depth, soil moisture with the highest percentage is Site IB, with 91.35% (Table 2); this sample was totally saturated with water and was virtually all organic material. Unlike Site IB, the Site I and II had a lower percentage of moisture.

4. Conclusions and Recommendations

The Maracayo Mangrove or the wetland of Camuy reflects the hydrological changes by land uses that have suffered wetlands over time, mainly during the twentieth century in the Caribbean. A number of countries in the tropics have eliminated wetlands by drying and draining them, claiming that they are sources of disease, for later use in agriculture and for urban and industrial development.

In the case of the wetland of Camuy, the establishment of drainage canals in the early twentieth century for agricultural development of the area, the subsequent abandonment of agriculture by the end of the 30s and the elimination of the sand dunes in the late 60s and 70s, established hydrological alterations that changed the original marshy conditions and encouraged the development of a mangrove wetland long term. The temporal and spatial dynamics of hydrological changes and increased marine influence, which led to salinization, promoted and continues to promote the establishment of mangroves in the area, causing a change in the wetland ecosystem. Because of these changes, mainly hydrological, ecosystem change is constant.

Global climate change will affect regional precipitation patterns in the Caribbean, with drying projections of -10 to -50% present precipitation [32, 33], and specifically for Puerto Rico (-10 to -30%) [34, 35], but also annual spatial precipitation patterns

directly affecting the hydrological dynamics of the wetland and therefore the vegetation composition found in it. Comparison between salinity data taken in 1979 and in the present, shows the changing rainfall patterns which reduces the surface presence of salinity in the present.

The continuity of ecophysiological and hydrogeological studies in this area are needed to understand the dynamics of this ecosystem in its fullness in the present and to predict its composition in the future, considering the rise in sea level, alternating patterns of freshwater availability and other environmental conditions that are changing due to climate change.

The social relevance of the wetland in the communities surrounding the mangrove presented is very evident in the interviews and oral history collection. Many camuyanos have a connection to the mangrove. With the changes that it has suffered and will suffer, a further study should be made on the intrinsic relationship between human beings and the landscape within a much broader sense than that occurred in this study.

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Appendix

1. Questionnaire used for this study

The Mangrove of Camuy: The land use history of the Maracayo Mangrove in Camuy, Puerto Rico

Instructions: Please fill in the following table and questions. You can write everything you think that answers the question and more.

Sex		F
		M
Age		40-49 years old
		50-59 years old
		60 years old or more

How many years have you been living in Camuy?

In which part of the municipality of Camuy do you live in?

Barrio Pueblo

Barrio Membrillo

Do you know about the mangrove area in Peñón Brusi?

At some point, was this area used as a landfill?

At some point, was there sand extraction in the sand dune area?

At some point, was it used for agriculture? Was there a sugarcane plantation?

In which areas do you know that sugarcane was cultivated in Camuy?

Do you know someone or have a family member that worked in the cultivation of sugarcane in Camuy?

If so, what anecdote did this person say about it?

Have you noticed how uses of this area have changed in the mangrove have changed with time? Does it include one or more of the following?:

Fishing

Fresh water source

Landfill

Agriculture

Livestock

2. Cadastral number of the Finca Nolla provided by the website of the Planning Board of Puerto Rico