A GIS ANALYSIS OF THREE BIOLUMINESCENT BAYS, VIEQUES, PUERTO RICO

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INTRODUCTION

The southern coast of Vieques, Puerto Rico is home to numerous bays containing the bioluminescent dinoflagellate *Pyrodinium bahamense* var. *bahamense* in varying concentrations. These bays include Puerto Ferro, Bahia Tapon, and Mosquito Bay. Mosquito Bay contains the densest population of these organisms, possibly because of the narrow channel connecting it to the ocean (Bernache-Baker, 1995). The channel shape may minimize the volume of seawater that enters the bay each day, and limit the dinoflagellates leaving the bay, stabilizing their population (Seliger et. al, 1970). The purpose of this study was to analyze size, character, and change of the bays using historical photographs and remote sensing data. This data can eventually be compared to historic populations of dinoflagellates in the sedimentary record to determine the effect of changes in bay shape on population.

Although a present-day GIS of the study area was produced by the National Geospatial-Intelligence Agency in 2003, it focuses on Mosquito Bay (Mitchell, 2005). To expand the existing analysis, the modern characteristics of Puerto Ferro and Bahia Tapon were analyzed, including bathymetry and channel characteristics. Bioluminescent populations can be affected by watershed conditions, so the watersheds of all three bays were mapped. Also, preservation of the bioluminescence depends on minimal artificial lighting, which can be analyzed with topographic and land use data. Changes in land cover, specifically the growth of urban areas and mangroves, were qualitatively analyzed. Mangroves were analyzed because it is hypothesized that the decay of mangroves may provide nutrients vital to the dinoflagellates (Bernache-Baker, 1995). Current land use was compared to historic land use practices. This study helps show how the bays may respond to future development and land use changes.

METHODS

Depth of Bahia Tapon and Puerto Ferro was measured on transects of each bay by kayak. With a sonar device at more than 100 points with an accuracy of ± 0.1 m. A bathymetric map of Puerto Mosquito was created in 2003. The coordinates of the depth measurements were recorded on a Thales Mobile Mapper® GPS unit. The Bahia Tapon depth readings were adjusted for tide using an interpolation procedure. Depths were adjusted to mean low water values using the time of measurement compared to tidal fluctuations recorded at a stationary YSI Sonde® in the bay mouth. The depths of Puerto Ferro were not adjusted because times were not recorded with all of the depths, which is one source of error in Puerto Ferro's bathymetry map. Error in this method also occurs because the YSI Sonde was placed in the center of the bay, and the tide is not uniform throughout the bay.

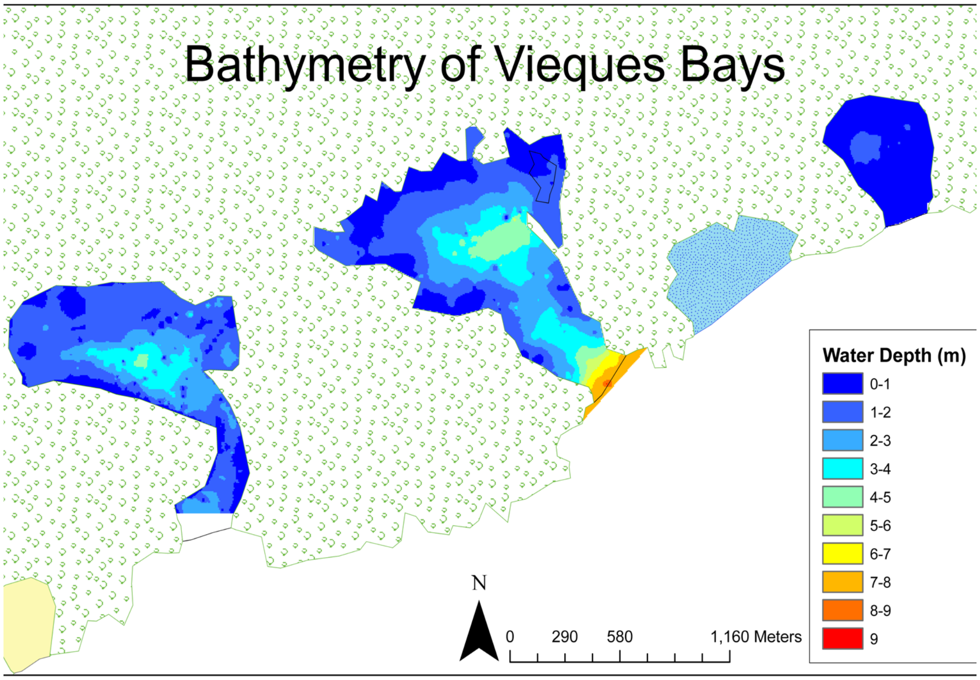


Figure 1: Bathymetric map by Inverse Distance Weighted interpolation.

Aerial photograph mosaics were obtained from the Caribbean Office of the United States Fish & Wildlife Service. Black and white photographs from 1936, 1959, 1964 and 1994 and color images from 1962, 1970, 1983, 1985, and 2000 were used. The images had been georeferenced to UTM 1984 WGS Zone 20N. All of the images had a one meter resolution. The error in referencing the photographs was estimated to be ±10 meters by digitizing the same road intersection in every image and measuring the distance between the two points furthest apart. In addition to aerial photgraphs, a 2005 ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image was obtained from the United States Geological Survey (NASA, 2005). The resolution of this dataset was 15 meters for the visible and near infrared bands and 30 meters for the short wave infrared bands.

GIS ANALYSIS

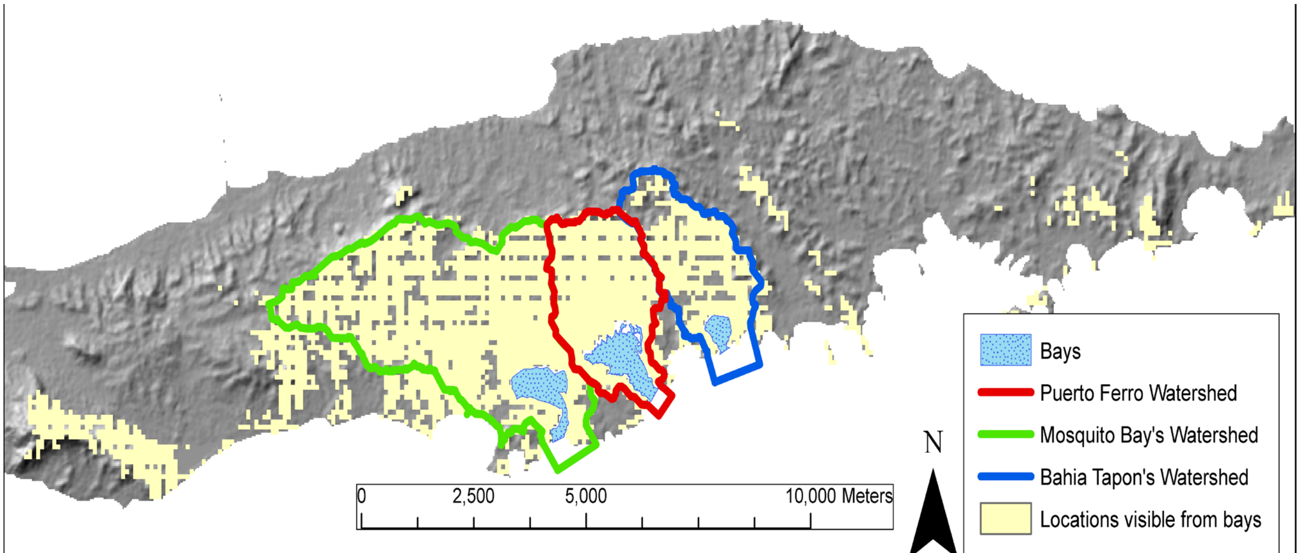
Bathymetric maps of Puerto Ferro and Bahia Tapon were created by importing the GPS locations of each depth measurement into ArcMap 9.1 (ESRI, 2005). The bathymetry of each bay was interpolated from the points using inverse distance weighting (IDW), (Figure 1), which creates a surface by assigning cell values based on values of nearby samples, with the weight of each sample being a function of the inverse distance the cell is from that sample (ESRI, 2005). This method of analysis was used because it had produced the Mosquito Bay bathymetry raster (Mitchell, 2005). The bay volume and surface were calculated below a reference plane of zero. Error in the bathymetry maps results from human error in using the depth sounder, insufficient transects, and error inherent in the IDW method.

Cross sectional areas of the bay mouths were measured to determine how much water each bay exchanges with the ocean. Piecewise integration of east-west bathymetry profiles at the most narrow channel openings that consisted of one hundred points at equal intervals yielded the area of each bay inlet.

Polygon shapefiles of each bay were digitized on screen for each image year by tracing the coastline of each bay, and the surface areas of the bays were calculated. To determine if the width of bays mouths changed over time, the shortest of numerous lines drawn across each bay mouth was recorded as the bay opening for each image year. When digitizing, error resulted from limited feature recognition due to the resolutions of the photographs. It was often difficult to discriminate between water and mangroves in the black and white photographs. Therefore, error in the shoreline is estimated to be ± 10 meters. In addition, the tidal cycle when each picture was taken is unknown, which adds an undetermined error.

Visibility and watershed boundaries were derived from 1 second Shuttle Radar Topography Mission (SRTM) elevation data (USGS, 2006).

A line of sight analysis uses topography to determine which points can be seen from the bays (Figure 2). After degrading the resolution of the DEM to 90 meters to speed processing and the viewshed tool was applied to each bay using a feature layer of all the points in the bay. These maps were then combined to produce a map of the viewshed for all three bays. Watersheds of each bay were determined from the pit-removed 30 meter SRTM using the Basin function of ArcMap (Figure 2), and the area of each watershed was calculated.



	Water volume (cubic m)	Cross Sectional distance (m)	Cross Sectional Area (square m)	Surface Area (square m)	Average Depth (m)	Watershed Area (square m)
Bahia Tapon	160605	148	49	248479	0.65	6136000
Puerto Ferro	1894310	228	1104	856167	2.21	6786000
Mosquito Bay	1333747	91	115	912370	1.46	16736000

Figure 2: Map of Watersheds and Viewshed of Bioluminescent Bays. This figure also contains a table of current conditions for each bay.

Land use on Vieques has changed dramatically from 1936 to the present, especially from United States Navy activities on the island. Urban growth and military land use were the land cover types considered in this study. For a primary analysis, locations that exhibited a qualitative change over time were observed and recorded (Figure 3).

Ferro's cross sectional area (1104 m_2) is an order of magnitude larger than Mosquito Bay. Mosquito Bay and Bahia Tapon both have cross sections that are asymmetrical, while Puerto Ferro's channel opening is symmetrical.

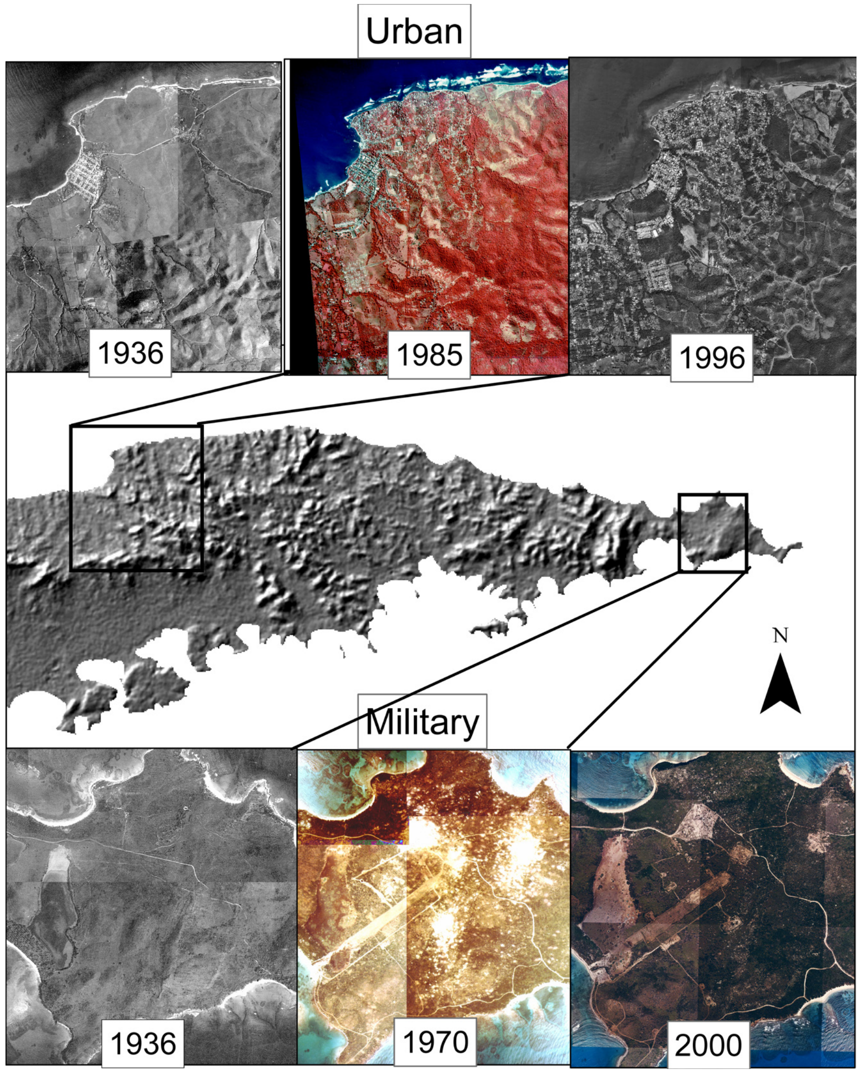
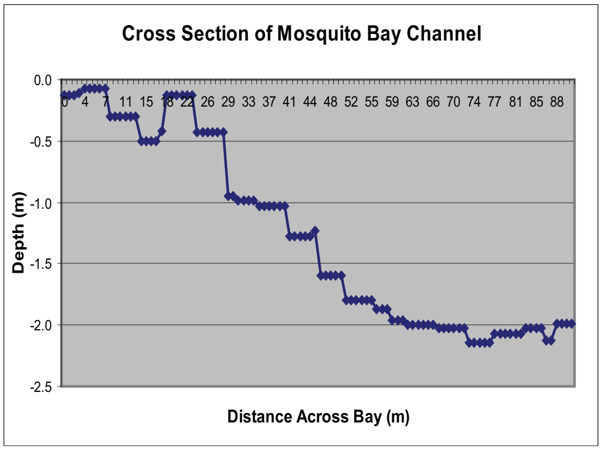


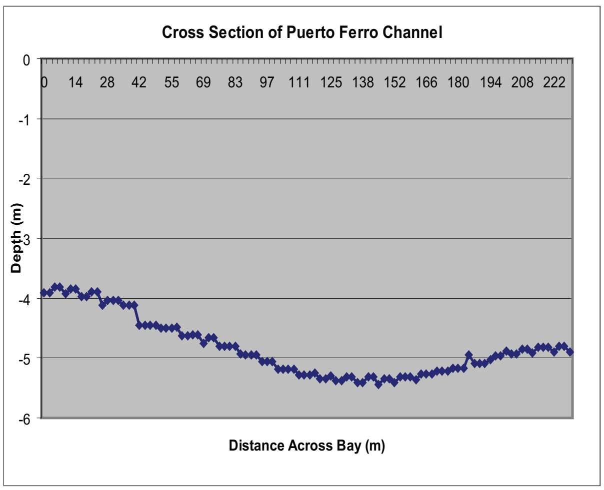
Figure 3: Land cover changes on Vieques.

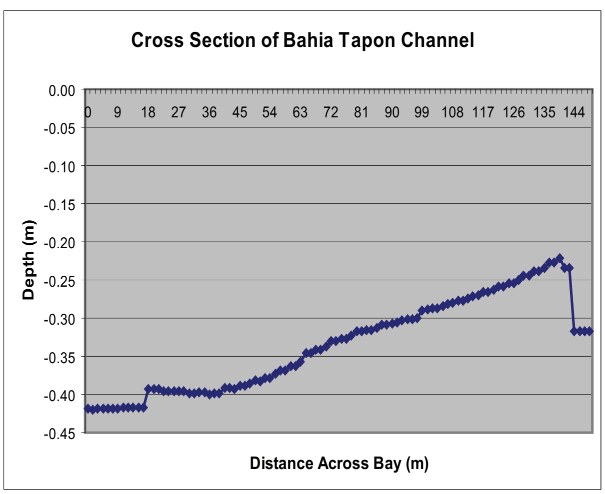
RESULTS

The width and cross sectional area of the bay mouths differ considerably (Figure 3). Bahia Tapon's channel opening has a cross sectional area of only 49 m_2, which is less than half of the size of the opening of Mosquito Bay. Puerto Ferro and Mosquito Bay have approximately the same surface area, but the average depth of Puerto Ferro is almost a meter greater (Figure 3). Bahia Tapon is the shallowest bay and has the smallest surface area, but its channel opening is wider than that of Mosquito Bay.

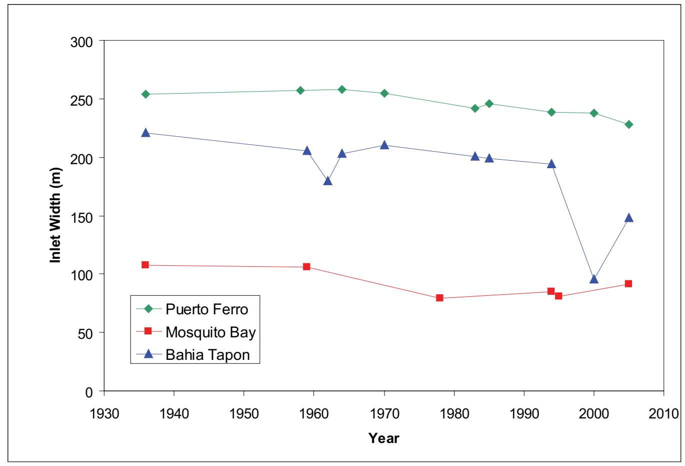
Figure 4: Graphs of cross sectional profiles for all three bays.







Moreover, Bahia Tapon has a relatively uniform depth compared to the other two bays. Mosquito Bay consistently has the smallest channel opening and the maximum depth is not in the channel, unlike Bahia Tapon and Puerto Ferro. Puerto Ferro's bay area and mouth transect lengths are stable over time. From 1936 to 2000 the bay area decreased by approximately 30,000 m2, which is only a 3.7% difference over 64 years and did not occur in one time interval.



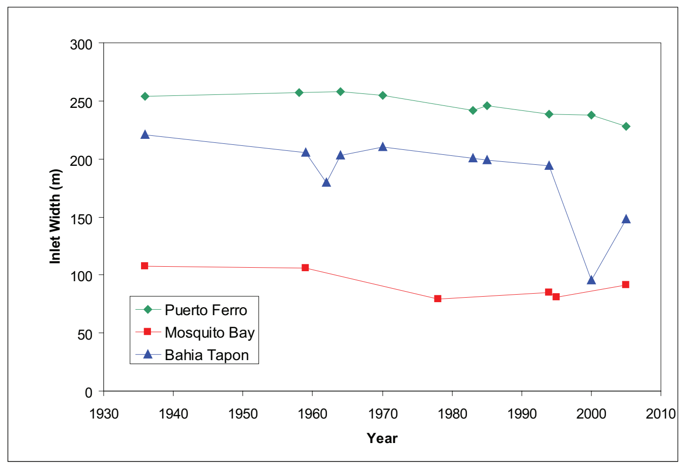


Figure 5: Results of the bay area and channel distance measurements over time. The top graph is area versus time and the bottom graph is inlet width versus time.

The results of the watershed analysis (Figure 5) show Mosquito Bay's watershed includes an area that is more than twice the area of the other two watersheds. Mosquito Bay's watershed also includes areas that drain into the lagoon and salt flat adjacent to Mosquito Bay. All of the watersheds slope south towards the bays.

The range of elevation in all of the watersheds is approximately 100 meters. The Puerto Ferro and Bahia Tapon watersheds include land that is primarily part of a nature preserve, while Mosquito Bay's watershed has agricultural land and developed areas including houses and paved roads.

Land use has shifted from primarily agricultural use to military or non-agricultural use. Much of the area that was farmland in 1936 remained treeless until 1970 and was completely reforested by 1983. The eastern portion of the island began to show evidence of bombing in 1959, and the 2005 ASTER image still shows scars from the military activity. Urban areas have grown considerably since 1936, especially the town of Esperanza located on the southern coast of the island. The town of Isabel II, on the northern shore of the island, has expanded since 1936. Along with the growth of towns, number of the roads present on the bays increased in both military and non-military areas, including many in the watersheds of all three bays.

Discussion

The values in Figure 5 suggest that there has been no significant change of size or shape in the three bays over time. In general, the bays changed gradually in the period from 1936 to 2005. The area of Mosquito Bay decreased almost 10,000 m2, which is a significant change, likely caused by the mangroves extending into the bay. This change would not have affected Mosquito Bay's exchange of water with the ocean because the mouth width stayed constant, and therefore the nutrient exchange with the ocean could have remained constant. These results suggest that *Pyrodinium bahamense* was not affected by changes in the hydrography of this bay, except for bathymetry, whose effect in unknown. All three bays exhibit slight changes in size or shape, but they were gradual and therefore likely did not affect the exchange of water with the ocean.

The width of the bays mouth can control how bay water residence time. Although the measurement of the mouth of Bahia Tapon was smaller in 2000 than any other year, this could be attributed to tides. A sand bar at the eastern portion of the mouth may be subaerial during low tide. It was visible underwater in photographs of other years and above sea level in 2000. If only the 2000 image was taken at low tide, then it can be said that this change in bay mouth length does not affect the hydrodynamics of the bay. Therefore, nutrient cycling and water residence time were most likely not affected by the apparent change in the width of the mouth.

Other studies could supplement this work. It would be useful to quantify land use change over time. The mangrove growth over time should be determined because of the hypothesis that nutrients from decaying mangroves are necessary for *Pyrodinium bahamense*. To differentiate between mangroves and other vegetation, the ASTER data can be classified or the perimeter of the digitized outlines can be studied to determine the change in mangroves. Also, historic bathymetry maps could help determine if the bay volumes have changed significantly. Until the changes in the population of dinoflagellates are found for Bahia Tapon and Puerto Ferro, the effect of bay hydrography changes on populations cannot be determined.

The results of this GIS analysis can be used to help preserve all three bays, especially Mosquito Bay. The watershed of Mosquito Bay is more than twice as large as the other two and includes agricultural and urban areas. To preserve the right balance of nutrients flowing into the bay, land use practice in the entire watershed might have to be regulated. A future land use plan can be developed by combining the viewshed data with the watersheds to determine which sites are not ideal for development.

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