HISTORICAL DEVELOPMENT OF THE MUNICIPAL LANDFILL IN THE EASTERN BORDER OF THE LUIS PEÑA CANAL RESERVE IN THE MUNICIPALITY OF CULEBRA, PUERTO RICO AND ITS POTENTIAL IMPACT ON THE RESERVE

Final Report submitted to the Department of *Natural and Environmental Resources* of the Commonwealth of Puerto Rico in fulfillment with Task CRI-9 PR CORAL REEFS AND WATERSHEDS STRATEGY of the *Conservation and Management of Puerto Rico Coral Reefs proposal*

By

José Norat, Ph.D.

Department of Environmental Health
Graduate School of Public Health
Medical Sciences Campus
University of Puerto Rico

and

Hernando Mattei, Ph.D.

Department of Social Sciences
Graduate School of Public Health
Medical Sciences Campus
University of Puerto Rico

September, 2007

This project has been sponsored by the *Department of Natural and Environmental Resources, through the Conservation and Management of Puerto Rico Coral Reefs* National Oceanic and Atmospheric Administration *Grant award #NA05NOS4191007*

INTRODUCTION

Study Objectives

This report presents the results of the field and documentary evaluation conducted of the Luis Peña Channel No-Take Natural Reserve and at the site of the existing sanitary landfill facilities of the Culebra, Puerto Rico municipality during 2006-07. The principal objectives of this phase of a two-phase study were to:

1) analyze the history of the Culebra sanitary landfill and its effects on the adjacent shoreline using remote sensing data,
2) estimate the sanitary landfill's potential for erosion and sedimentation impacts on the Luis Peña Channel,
3) collect preliminary data on the pollution potential of the landfill's leachate on the Channel, and
4) evaluate conditions of coral reefs at monitoring stations located along the Channel.

Site description

Culebra Island is one of a series of adjacent islands located to the east zone of Puerto Rico. These islands are part of the Puerto Rico municipalities where the most prominent are Vieques and Culebra. Culebra is located at least 27 kilometers to the east of Puerto Rico and 19 kilometers to the east of Virgin Islands. Its size is 12 kilometers length by 6 kilometers wide for an approximate area of 26.5 square kilometers. The existing municipal sanitary landfill is found at Punta-Bahia Tamarindo located 3,000 meters northwest of the Culebra downtown area, bordering the Luis Peña Canal Reserve and 500 meters southwest of Laguna del Flamenco.

Landfill operations in Culebra Island, Puerto Rico, have been identified as one of the most significant environmental threats to marine communities located within the Luis Peña Channel No-Take Natural Reserve (LPCNR) (Hernández-Delgado, 1994, 2003b, 2004).

One of the main concerns is related to the possibility of leachate contamination migrating from the higher zones of the sanitary landfill to the lower areas. If occurring, a continuation project will characterize the contaminant concentrations within the Luis Peña Canal Reserve from samples collected along the coral reef monitoring stations and compare those results with the well monitoring samples.

The landfill was established during 1984 in Flamenco Ward at approximately 25 m from the shoreline of Bahía Tamarindo within the LPCNR. Biological communities within the reserve support an outstanding biodiversity representative of the northeastern Caribbean region (Hernández-Delgado, 2000, 2003; Hernández-Delgado et al., 2000; Hernández-Delgado and Rosado-Matías, 2003). Biological communities located in Bahía Tamarindo and Punta Rompeanzuelo, in close proximity to the landfill, are also highly diverse and highly structured (Hernández-Delgado, 1994, 2003a). However, water quality degradation has been pointed out as one of the causes of coral reef and fish community declines in Culebra (Hernández-Delgado and Sabat, in review; Hernández-Delgado et al., in press). The Department of Natural and Environmental Resources (DNER) is highly concerned with the potential impacts of the Culebra landfill operations on the local marine communities. But in spite of the ecological, economic, aesthetic and touristic significance of Bahía Tamarindo marine communities, there is no information regarding environmental impacts of landfill operations.

TASKS PERFORMED

Administrative Tasks

Dr. José Norat has been in charge of administrative matters, study design and partial report preparation. Dr. Hernando Mattei carried out analysis of georeferenced demographic data of the land near the study areas to consider other non-point pollution sources. He has also been in charge of partial report preparation. The image analysis expert contracted was Dr. Maritza Barreto, from University of Puerto Rico, Río Piedras Campus). For the services of geologic and geographic information systems analysis, the experts contracted were Dr. José Seguinot, University of Puerto Rico, Medical Sciences

Campus and GIS consultant Nilda Luhring. They analyzed the geology, slope, soil and erosion conditions at the landfill. The services of coral reef expert Dr. Edwin Hernández, University of Puerto Rico, Río Piedras Campus, were contracted also. A contract was signed with the geotechnical engineering firms of Víctor Ortiz, P.E., GEOCOM, and Alchem Laboratories to carry out well monitoring within the landfill. Integrity tests of existing wells were carried out. Sample analysis for general organic and heavy metal pollutants of well samples were carried out by the firms. Substances that were detected will be part of the water quality parameters tested in phase II of the coral reef study. A formal request was made to the Mayor of Culebra Municipality to obtain the permit to sample leachate from the Culebra landfill.

Data Acquisition

Historic aerial photographs and images of the Luis Peña Canal Region were acquired and analyzed for historical changes in landfill’s location, extent, activities and for sedimentation influence on the Canal. A geographic data base with the environmental variables of the Culebra's landfill study was prepared. This included the following geodatabase layers: soil types, geologic regimes, topography, hydrographic contours, coastline, local georeferenced aerial photo (vegetation, landfill), roads, and political boundaries. These layers allow an analysis of association between the physical conditions of the landfill, the water runoff and the topography.

Field Work

Visits to the coral reef study areas were carried to evaluate coral reef conditions at the station closest to the landfill. Other stations in the Channel were evaluated for comparison. Dr. Hernández, along with two graduate students, carried out quantitative and qualitative measurements of water quality, species diversity and other parameters indicating coral reef health and conditions at the various stations in the Channel. The landfill was also visited and a geotechnical study was carried out. Goundwater samples were taken at the landfill monitoring wells for laboratory analysis.

SUMMARY OF RESULTS

In summary, no negative impacts of the Municipality's sanitary landfill were observed in the coral reef formations at the site near the Culebra landfill. Some historical changes were observed in the morphology of the Channel coast near the landfill site. Coral reef biologic communities are diverse and did not differ significantly between observation and sampling sites. Neither were other signs of impacts form leachate pollution observed at the site of the landfill's runoff discharge point into the Channel. However, leachate was observed within the landfill and a threat of pollution of the Channel exists. It is recommended that a clay dike be constructed along the perimeter of the leachate zones in the landfill as a precautionary measure to control runoff migration and prevent the possibility of leachate contamination of the Luis Peña Canal Reserve and Punta Tamarindo coast. Following is an individual summary of the study design and principal findings of each of the different components of the overall study.

Summary of Component 1- Remote sensing analysis of the landfill site at Culebra.

This component of the study consists of a geomorphologic assessment of coastal geomorphic changes and nearshore sediment transport from Punta Tamarindo Grande to Punta Tamarindo at Culebra, Puerto Rico, using remote sensing techniques. It includes an evaluation of historical aerial photos and images from 1964 to 2004 period and of morphology changes in beach plains, subaerial fringing reef structures and nearshore geomorphic features. The study looks for the association between these changes and the existence of the municipal landfill near this area.

The landfill is located near a main drainage line of the island, a characteristic that may produce major runoff during major rainfall events transporting materials and sediments from the landfill site to the Punta Tamarindo shoreline and its south west shoreline area, directly affecting the study area. Changes such as an increase in landfill section and/or barren land during the 1996 to 2001 period were observed. A small water body was identified at the southeast of the landfill site from 1996 to 2001.

Changes in beach plain areas were observed in the aerial photographs during the 1981 to 2004 period. Major changes were found in beaches located to the west side of Punta Tamarindo and Bahía Tamarindo near the landfill site. The study area showed intermittent and permanent beach plain along the coastline from 1964 to 2004. Subaerial reefs structures were identified using vertical aerial photographs for 1964, 1981, 1996 and 2005. A reduction of reef structure observed in 2005 at Punta Tamarindo near the landfill site may be related to high sediment concentration in the nearshore coming from land sources that does not permit the visualization of reef structure for this period. Erosion was mainly observed from 1981 to 2004 at Punta Tamarindo near the landfill site. Major morphological changes were identified in this site during the 2001 to 2004 period. Suspension of materials from land sources along the shore path were observed with highest concentration identified in the 2004 period. Higher suspended material concentration (maybe sediments) can affect marine ecosystems as coral reef, seagrass and algae communities producing a decrease in biogenic sediment production in the nearshore area. In conclusion, the landfill site showed morphological changes for the periods between 1981 and 2004. Beach erosion was found in subaerial plains located near Punta Tamarindo from 1981 to 2004. Beach erosion may be associated with storm occurrence and landfill activities in the area. Loss of beach sand produced a major suspended sediment transport in the longshore direction during the 2001 to 2004 period.

Summary of Component 2- Analysis of soil type and susceptibility to erosion of Culebra, including the landfill site

This analysis concludes that this landfill is located in a volcanic rock formation known **as Tks** from the upper cretaceous (135 millions years ago). This formation is composed of volcanic rocks, sandstone, limestone, conglomerate, lava and volcanic tuff. Some marble has been deposited in the marine environment and the rock exposed has been weathered by the ocean and climate. Slope and topography is very steep (more than 15 %) forming good conditions for landslide, weathering and erosion. Although no water bodies were recognized in the area, several runoff channels exist moving in the direction of the coast. The dominant soil type is the Arcilla Daguao (DeE2). This soil has a very low production capacity, and is composed mainly of rock and is developed in arid conditions, where precipitation is less than 10 inches annually. The average temperature of this soil is 79 °F.

Based on the hard conditions of the underground volcanic and sandstone rocks a very low movement of the underground water is expected. On the other hand, this movement increased by the effect of the topography and the inclined position of the rock stratification. The anticline formation of the mountain where the landfill is located has facilitated the movement toward the east side of the landfill. The eastern aspect of this mountain and the cliff formation in the west direction (where the Luis Peña channel is located) reduces the possibility of underground leachate movement toward the west direction.

The soil type and susceptibility to erosion of the study area was analyzed. The following parameters were considered: slopes, permeability, runoff, soil depth, depth of water table, availability of water and shrink-well potential. The soil types of the study area used in the analysis were Descalabrado clay loam (DeE2) and Amelia gravelly clay loam (AmC2) from the Amelia series. The Descalabrado clay loam has a 20 - 40% slope and is located in the slopes of the mountains and in the top of the hills of semiarid volcanic soils. Other characteristics of this type of soil are steep slopes, rapid runoff, shallowness from bedrock and hazard for erosion. It shows a permeability of 0.6-2.0 inches/hour hour (moderate); available water capacity range from 0.10 to 0.15 inches/inches of soil; low corrosivity for concrete and high corrosivity for uncoated steel; moderate shrink-swell potential; it has a depth to seasonal high water table of more than 6 feet (rapid runoff); the depth of the bedrock is from 1 to 1.5 feet. The DeE2 soil is susceptible to erosion. The Amelia gravelly clay loam has a 5 - 12% slope and is located in the foot slopes in semiarid areas. This soil has the characteristics of the Amelia Series, which are deep soils, have good drainage and a moderate permeability.

To determine the susceptibility to erosion of these soils with higher precision, a revised version of the Universal Soil Loss equation was used. A=RKLSCP, in which A is the annual soil loss, R is the factor for climatic erosion, K is the factor that measure the soil erosion in standard conditions, L is the factor of slope's length, S is the slope factor, C is the land cover and P is the practice for conservation. Each one of the variables mentioned was analyzed for each soil type in the study area. Soil type DeE2 showed susceptibility for erosion. For soil type AmC2 the susceptibility for erosion couldn't be established.

The use of Universal Soil Loss Equation yielded the following results for the two soil types associated with Culebra's landfill.:

Soil Type	R	K	LS	C	P	A
AmC2	250	0.24	3.25	0.003	1	0.585
DeE2	250	0.24	8.72	0.003	1	1.570

The table shows that for most of the landfill's area, covered by the soil type DeE2, a result of approximately 1.57 tons/acre /year of sediment is transported downslope. Therefore its susceptibility for erosion can be established. The soil type AmC2 shows a result less than one (1), therefore it can't be established that the susceptibility for erosion is comparable. However, it is important to state that a characteristic of the soil from the Amelia Series is that it tends to erode.

Summary of Component 3- Geotechnical field evaluation for determination of superficial leachate movement at the Culebra's sanitary landfill

The objective of this component of the investigation was to observe the topography, area and superficial soil conditions of the site where the municipal sanitary landfill is located in order to identify those areas with a possibility of creating a leachate impact on the nearby Luis Peña Canal Reserve and to the Punta Tamarindo coast. Also this evaluation included the field identification of a series of groundwater and methane gas monitoring wells; determine their locations and structural conditions within the sanitary landfill site; and to present findings related to the presence of leachate and its impact by leakage, infiltration or runoff to the Luis Peña Canal Reserve and its related coral reef life.

According to the PREQB map *Geologic Map of the Culebra Quadrangle*, the site is underlain by volcanic rocks corresponding to the TKs Formation. It consists of sandstone, siltstone, conglomerate, lava, tuff, and tuffaceous breccia all of late Cretaceous Age. This formation covers about 90% of the Island of Culebra and is located predominantly around its west, south and east areas. The northern zone of the island is covered by alluvium, diorite and volcanic toba.

In March 1992 an Environmental Impact Study of the landfill's expansion (DIA Final, by its Spanish acronyms) was submitted by the Municipal Administration of Culebra to the Puerto Rico Environmental Quality Board (EQB) and the Fish and Wildlife Service (FWS) and others for comments. The document was entitled "Declaración de Impacto Ambiental, Ampliación del Vertedero Municipal de Relleno Sanitario de Culebra, Puerto Rico". Both agencies presented some recommendations requesting additional studies and changes in the proposed design of the sanitary landfill extension. The most prominent recommendation deals with the protection of the coast of Punta Tamarindo and Luis Peña Canal located to the south and east areas of the landfill against leachate.

On the basis of field investigation three (3) zones of potential leachate leakage were identified. These zones are identified in a figure as zones Z-1, Z-2 and Z-3. Zone Z-1 is located at the northeast area of the landfill where superficial leachate leakage was identified as evidenced by Photographs. Zones Z-2 and Z-3 are located to the south zone of the landfill and consist of concentrated leachate leakages facing an existing dirt road having a slope inclination of about 35 degrees going down to the east of the landfill. There in some instances it will migrate to the lower areas of the landfill heading to an existing pond close to the Bahia Punta Tamarindo and its coast, as show in Photographs. It is possible that in an event of heavy rains this substance will migrate to these zones creating an environmental impact to the area if some protection measures are ignored.

It is understandable that the municipal administration of Culebra is looking for funds in order to invest in the landfill improvements including its new expansion. But that process will take a long time and certainly some rain events will occur creating a potential threat to the Luis Peña Canal Reserve and the Punta Tamarindo coast. In order to implement remediative measures until the expansion occurs, it is recommended that a clay dike be constructed along the perimeter of the Zones previously mentioned so as to control runoff migration and prevent the possibility of leachate contamination of the Luis Peña Canal Reserve and Punta Tamarindo coast. A figure shows the proposed location of this earth dike and its recommended geometry.

If the sanitary landfill expansion is approved by the regulatory agencies it is recommended the implementation of all of the runoff water control and leakage management presented in the "DIA Final" document be implemented as soon as possible, specially the recommendations regarding leachate control close to the Luis Peña Canal and its coast.

Summary of Component 4- Biological characterization of coral reef communities adjacent to a municipal landfill, Luis Peña Channel Natural Reserve

Coral reef communities adjacent to the Culebra Island municipal landfill were assessed and quantitatively described for the first time to test for any potential landfill operation impact. Given the lack of long-term monitoring, and the resulting temporal and spatial constraints of this study, there were no signs of landfill impacts in adjacent coral reef benthic community structures. Coral reefs adjacent to the landfill still support a high biodiversity. However, reefs are showing signs of unequivocal decline associated with a combination of long-term regional (i.e. sea surface warming, coral bleaching, hurricanes, disease outbreaks) and local factors (i.e., sediment- and nutrient-laden runoff pulses, remote raw sewage impacts). Sediment-laden runoff pulses are often occurring in the landfill after heavy rainfall. Plastic bags and other plastic debris are frequently blown by the wind and end up at Bahía Tamarindo, but impacts of these were not quantified in this study. There is a need to use coral proxy signals (i.e., annual growth bands, humic acids, heavy metal accumulation) to test for any spatial and/or temporal variation in patterns of impacts.

The municipal landfill of Culebra, PR is located at approximately 25 m from the shoreline of Bahía Tamarindo by the Luis Peña Channel Natural Reserve (LPCNR). It was established during 1984 in Flamenco Ward. Biological marine communities within the reserve support an outstanding biodiversity representative of the northeastern Caribbean region (Hernández-Delgado, 2000, 2003; Hernández-Delgado et al., 2000; Hernández-Delgado and Rosado-Matías, 2003). Impacts to the reserve's sea grass and coral reef communities due to sediment-laden runoff impacts from the landfill have never been quantified, but they have been documented. The objective of this Phase I report was to produce a biological characterization of coral reef communities adjacent to the Culebra Island landfill, within the LCNR.

The methodology for this part of the study consisted of the study of 4 coral reef locations within LPCNR: one impact site (Punta Rompeanzuelo), and 3 control sites (Arrecife El Banderote, Punta Tamarindo Chico, Cayo Luis Peña-north coast). Benthic surveys of coral reef communities were carried out to test for significant spatial pattern in the structure resulting from potential landfill-based pollution. The survey was performed by six replicate 30 m-long point-count transects randomly sampled using digital video imaging at the four study locations. This approach provided baseline information regarding the actual condition of coral reefs. It also made possible a detailed biodiversity assessment of the species composition of the area.

The coral reefs were assessed for any disease or adverse vitality conditions and sources of recent mortality were identified whenever possible. The differences among the sites were tested with a one way analysis of variance (ANOVA) and/or Kruskal-Wallis non-parametric ANOVA. Changes in community structure were tested by means of multivariate statistical tests. Community matrices were compiled and imported into PRIMER ecological statistics software package for multivariate analysis (Clarke and Warwick, 2001). Mean data from each site were classified with hierarchical clustering using the Bray-Curtis group average linkage method (Bray and Curtis, 1957) and then ordinated using a non-metric multidimensional scaling plot. Spatial variation patterns were tested using PRIMER's multivariate equivalent of an ANOVA called ANOSIM. Key taxa responsible for spatial variation in community structure between sites were determined using the SIMPER routine.

Results showed a high biodiversity and importance of the coral reef community including critical habitat for the endangered green turtle, *Chelonia mydas*. Results demonstrated that no significant difference was found in coral reef species richness or colony abundance between areas. Percent partial colony mortality was not significant among sites (Figure 20), but percent recent colony mortality was significantly higher (p=0.0354) at AEB (8.5%) and the impacted site at PRA (7.4%). A SIMPER test revealed that benthic community differences between impacted PRA and AEB were mostly the result of higher % cover of sponges at AEB.

There was no evidence of direct impacts of landfill operations affecting the existing community structure of coral reefs adjacent to the landfill area in PRA. Existing differences among sites are largely the result of physical and oceanographic differences among sites. Actual conditions of coral reefs reflect basically similar patterns across sites, regardless of the distance from the landfill, suggesting that factors affecting corals are of larger geographical scales. There was evidence of recent coral mortality during 2006 and 2007 at each site as a result of the 2005 unprecedented sea surface warming of the northeastern Caribbean that produced a mass coral bleaching event, and the subsequent mass coral mortality that occurred within the next year and a half.

There are recurrent raw sewage pulses coming from Ensenada Honda downtown area through the Luis Peña Channel with almost every ebbing tide. Thus nutrient pulses are affecting all study sites, but particularly, PTC, AEB and PRA. T his may explain their slightly higher % macroalgal cover, and % cyanobacterial cover. The fact is that sediment-laden runoff pulses from the landfill site have been informed (Hernández-Delgado, 2003, 2004), but their impact in coral reef community structure, given the lack of long-term monitoring at adjacent sites, and the significant temporal and spatial constraints of this study, were not measured. For instance, during strong high pressure-driven easterly winds, plastic bags often are blown by the wind and carried away to the water, ending up suffocating isolated coral colonies, or laying down on seagrass bottoms that constitute designated critical habitats for a resident endangered green turtle (*Chelonia mydas*) population. This will require stronger compliance with existing regulations to prevent plastic debris to be removed by wind. Thus, determination of impacts will require further studies using coral proxy signals to address if there was any significant spatio-temporal pattern of landfill operation impacts on corals, part of the second phase of this study.

Summary of Component 5- Laboratory evaluation for the determination of superficial leachate constituents at the Culebra's sanitary landfill

In samples taken at the landfill's monitoring wells, the contaminants detected were Barium (0.043 ppm), Florurides (2.13 ppm), and Nitrates (7.4 ppm). Results shown for each parameter are averages of all readings. There was no detection of pesticides, PCB's, or volatile organics.

An assessment of landfill morphological changes, coastal geomorphic changes, and nearshore sediment transport from Punta Tamarindo Grande to Punta Tamarindo, Culebra, Puerto Rico using Remote Sensing techniques (1964-2004)

Maritza Barreto, Ph.D

Department of Geography
University of Puerto Rico
Río Piedras Campus

An assessment of landfill morphological changes, coastal geomorphic changes, and nearshore sediment transport from Punta Tamarindo Grande to Punta Tamarindo, Culebra, Puerto Rico using Remote Sensing techniques (1964-2004)

by

Maritza Barreto, Ph.D, Geological Oceanographer and professional geologist
University of Puerto Rico-Rio Piedras, Geography Department

Cielomar Rodríguez, assistant research, University of Puerto Rico-Rio Piedras Campus, Geography Department

ABSTRACT

This study includes an assessment of coastal geomorphic changes and nearshore sediment transport from Punta Tamarindo Grande to Punta Tamarindo at Culebra, Puerto Rico, using remote sensing techniques. The study includes an evaluation of historical aerial photos and images from 1964 to 2004 period. Geomorphic assessment includes an evaluation of morphology changes in beach plains, subaerial fringing reef structures and nearshore geomorphic features. An evaluation of landfill morphological changes also was included as a part of the assessment due to the possible impact of this landfill site over geomorphic component in the area. Results showed that major geomorphic changes in beaches and subaerial reef structure were found in the study area from 2001 to 2004. Significant erosion was identified near Punta Tamarindo for this period. Lack of beach plain caused that land derived sediment was transported from near landfill site to nearshore area at Punta Tamarindo.

STUDY AREA

The study area includes shoreline and nearshore area from Punta Tamarindo Grande to Punta Tamarindo located in the southwest area at Culebra Island. The area is also located in the north side of Canal Luis Peña. The study area includes a landfill site located in the north site of Punta Tamarindo (see Figure below).

Image from NOAA, 1999, Study Site Absolute localization:
18°20’N;65°19’O y 18°18’N; 65°18’O (Rodríguez, C., 2005)

METHODOLOGY

Geomorphic assessment in coastal components was conducted mainly using remote sensing techniques as analysis of both historical aerial photos and multispectral images from the study area. Included is the detailed activities carried out in this study.

1. Changes in landfill morphology using historical aerial photos and multispectral images

- Landfill morphology changes were evaluated using panchromatic aerial photo from 1964, 1981, 1996 and multispectral images from 2001 and 2004.
    - Photos were scanned at 900 dpi, 200%
    - A qualitative evaluation was conducted using these images due to differences in images sources.

- Photointerpretation was done to evaluate landfill changes.

2. **Evaluation of shoreline changes and subaerial reef structure from Punta Tamarindo Grande to Punta Tamarindo, Culebra, Puerto Rico.** (Methodology, analysis and map preparation done by Cielomar Rodríguez-research assistant-UPR-Geography department)

- Selection of vertical aerial photographs of 1964, 1981, 1996, 2005 at Minillas Office.
- Rectification of historical aerial photographs using ARC GIS
  - Rectification was done using IKONOS (ortho image 2001 with spatial resolution of 1 meter) as a base image. Reference Datum is UTM NAD83.
  - Aerial photographs were digitized using a flat bed scanner with resolution of 900 dpi by 900 dpi with magnification of 200%. Digital image were produced in TIFF format for ease of management. Total image digital size is 20 GB.
  - Images were rectified using ArcView v. 9.1
    - Images were compared to identified similar control points among photographs
    - Arc Map module was used for rectification process.
    - Twenty control points were used for rectification in this study. Some aerial photographs can not used in this study due to the constraint of the selection of control points for rectification. This occurred mainly to the northwest y southwest site of Culebra for 1964 and 1981.

Historical shoreline and subaerial reef structure changes were identified (done by Cielomar Rodríguez)

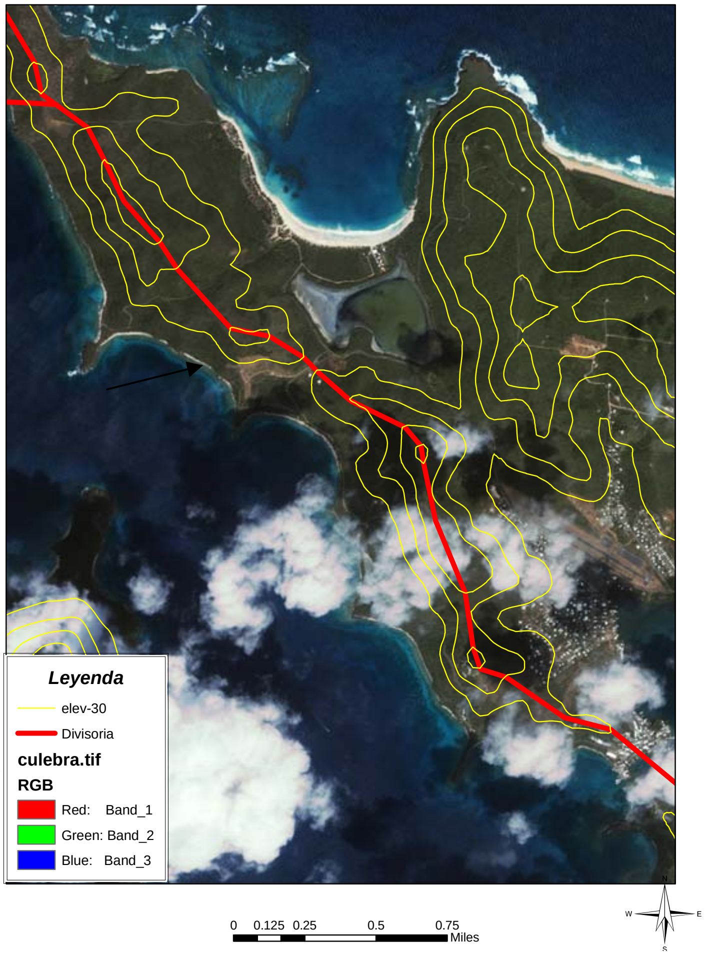
3. **Nearshore features and sediment transport delineation using multispectral images at Luis Peña Reserve**

- Selection of Panchromatic aerial photos, 1964, 1981, 1996
- Selection of multispectral Images (2001-2004)
    - IKONOS- 2001 spatial resolution-1 meter panchromatic
    - USDA multispectral image-2004 1 meter resolution; spectral resolution (red, blue and green)
    - Landsat Enhancement Thematic Mapper (30 meters spatial resolution and 4 spectral channel (visible-3channels and 1 near infrared), 2001 and 2003
- Pre-processing of Images
    - Atmospheric correction due to scattering using clear water pixel algorithm (for use in blue spectral channel)
    - Change of geographic datum NAD 83 (in USDA and IKONOS)
- Processing and classification
    - An unsupervised classification algorithm was used to identify geomorphic and landfill categories based on differences in brightness in the images.
    - Categories of surface features were identified including: longshore sediment transport, suspended sediments, land-derived material, beaches, and others.
    - Possible causes that produce suspended sediment in the area were evaluated.

RESULTS

Topographic Characteristics and evaluation of Landfill site at Culebra, Puerto Rico

Landfill site is located near Punta Tamarindo in the southwest of Culebra Island. The landfill site is located near the 30 meter contour elevation according to a map prepared by Rodríguez, 2007. Also, it is located near main drainage line (divisoria-red line) of the Island (see figure below). This topographic characteristic may produce major runoff occurring during major rainfall events that may transport material and sediments from the landfill site to the Punta Tamarindo shoreline and south west shoreline areas.



Topographic contour lines designed and prepared by Rodríguez, C., 2006

Changes in Culebra landfill site using historical aerial photo and multispectral images (1964 to 2005)

An evaluation of changes of the landfill site showed changes in shape and extension from 1981 to 2004. Major changes in the landfill site were identified from 1996 to 2001. These changes were observed as an increase in landfill section / and or barren land for this period. A small water body was identified to the southeast site of landfill site from 1996 to 2001.

Aerial Photo 1964

The landfill site is not found in the 1964 aerial photograph (see aerial photo from 1964). Aerial photography showed low density vegetation cover in the future landfill site. Low vegetation cover was also observed in the main drainage line located near the proposed landfill site. No major barren land cover was found at the site. A main road that extended from the Flamenco beach site to the proposed landfill site was found in the aerial photo for this period.

Aerial Photo 1981

Landfill site is found in the 1981 aerial photograph. According to the data the landfill site was opened during the first part of the decade of the 80's. The landfill site is oriented to the north of the main drainage line. An additional barren land was observed in the south site from the main landfill site. This barren land cover is not connected with the main landfill site. It is not clear if this new barren land area is caused by human activities, landslide or fire events (see aerial photo from 1981).

Aerial Photo 1996

The landfill site showed an orientation more to the south in this period compared with 1981 landfill location. Landfill site showed more extension to the southwest area. A barren land that appeared in 1981 aerial photo located near to Punta Tamarindo does not appear in the 1996 photo. Low density vegetation is observed in this area in 1996. Apparently a re-forestation event occurred in this site during the 1981 to 1996 period. New roads were observed from the main landfill site to the shoreline near Punta Tamarindo (see aerial photo from 1996).

Image 2001 (Ikonos)

Landfill site apparently expanded to the south and southeast during the 2001 period. A new barren land area appeared in the southeast coastline area of Punta Tamarindo. The expansion of this barren land area could be related with an extension of the landfill site or an occurrence of a landslide event that exposed the site to the southeast area of Punta Tamarindo. It is important to notice that the new barren site or landfill site is located to the south of a main drainage line. This may imply that material such as garbage and sediments that could be exposed in this new barren site could have been transported by runoff to the shoreline during this period (see aerial photo from 2001).

Image 2004 (USDA)

The landfill site extension is apparently smaller than the extension observed in the 2001 image. The landfill site observed is more compacted. The barren land site located near the main drainage line observed in 2001 image now appears less defined. This may imply that this barren site was not used only as a landfill site or other human activity. Another possibility is that site was affected by a reforestation event (natural or man induced).

Due to lack of information related of the development and history of the Culebra landfill during the last 40 years, we recommend that oral history studies be conducted to collect more information that helps to understand landfill changes in the area (see aerial photo from 2004).

Beach Changes (1964 to 2004) from Punta Tamarindo Grande to Punta Tamarindo, Culebra, PR

Major beach plain areas were observed in 1964 from Punta Tamarindo Grande to Punta Tamarindo. Loss of sediments was identified in the area during 1981 period. An increase in beach plains was measured for 1996 but erosion still appeared in the coast in 2004. Major losses of sand in beach systems were found during 2004. Loss of sand can be related with an increase of storm occurrences in the area and land cover changes. Minor subaerial beach plain changes were found on beaches located on the north site of Punta Tamarindo Grande. Major changes were found in beaches located to the west side of Punta Tamarindo and Bahía Tamarindo near to the landfill site. Major sand loss was measured in 1981 and 2004 photos.

The study area showed intermittent[1] and permanent[2] beach plain along the coastline from 1964 to 2004.

Intermittent beaches 1964

Three main intermittent beaches were identified (beach #10,11 and 12) in the photo for 1964 period. These were located near landfill sites.

Intermittent beaches 1981

An intermittent beach was found in the convex site of the lunate coastline from Punta Tamarindo Grande to Punta Tamarindo. This beach did not appear in other periods.

---

[1] Intermittent beaches are unconsolidated sediment plains that disappeared and appeared during the last 40 years in the area.

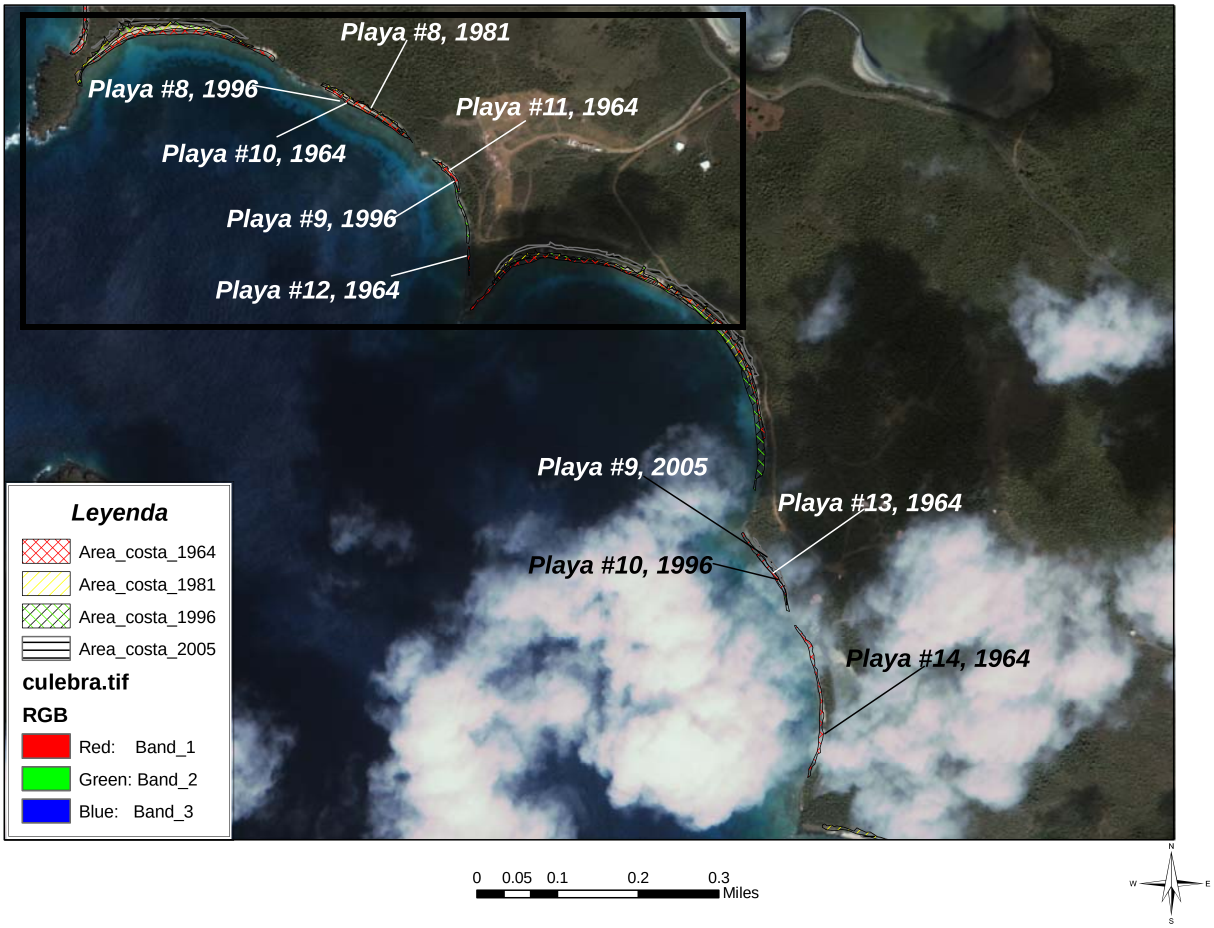
[2] A permanent beach is defined as a subaerial sediment deposits (gravel and or sand) that appeared in a coastal zone during a defined period.

Intermittent beaches 1996

Two intermittent beaches were observed from Punta Tamarindo Grande to Punta Tamarindo (Playa # 8 and Playa # 9) (see Figure below). These were located to the east site of Punta Tamarindo Grande and in the shoreline area near the landfill site.

Intermittent beaches 2004

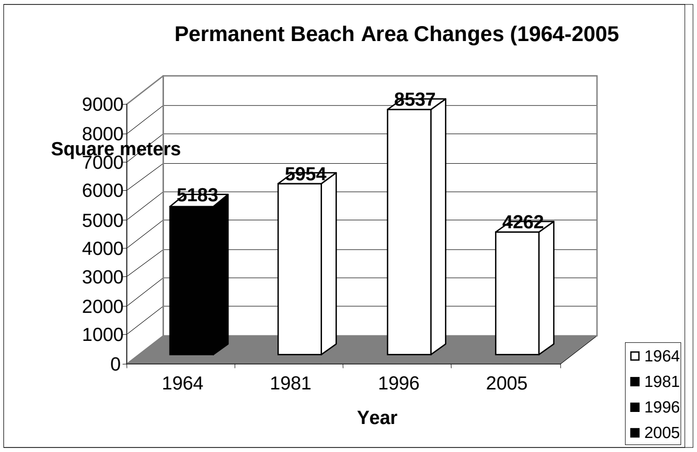
No intermittent subaerial beaches were found on the shoreline from Punta Tamarindo Grande to Punta Tamarindo in 2004.



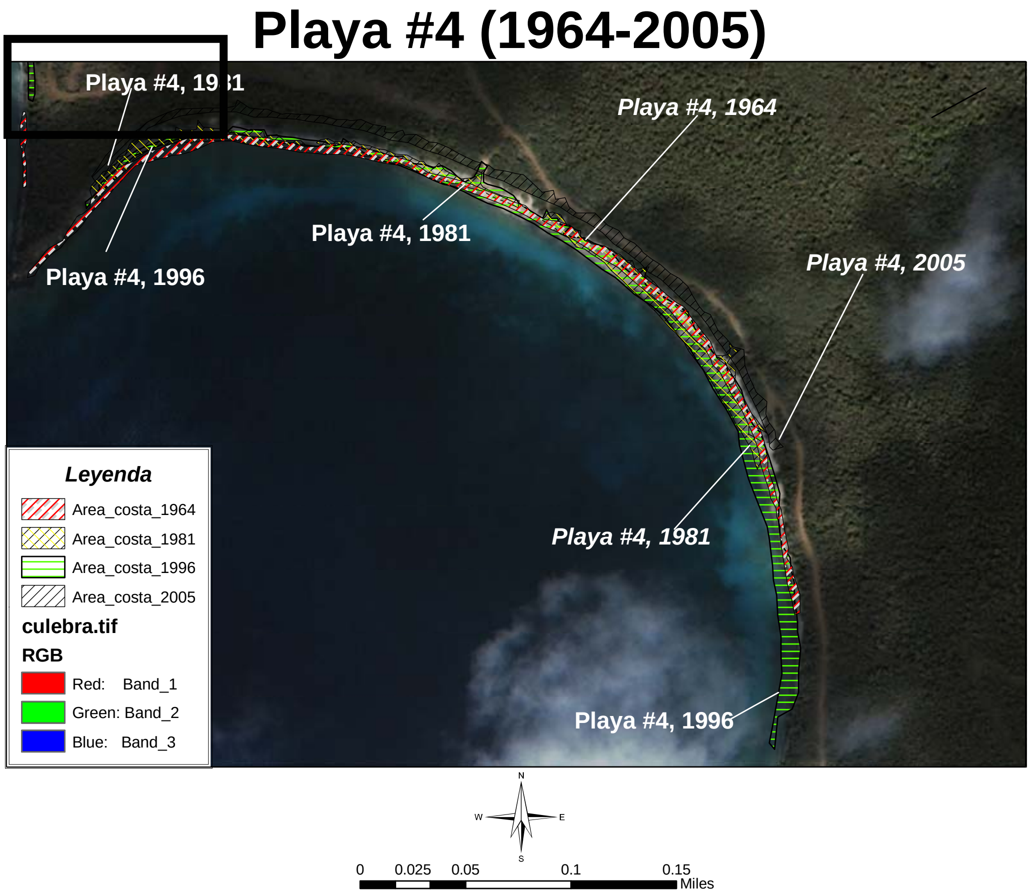
Intermittent beach plains identified from Punta Tamarindo Grande to Punta Tamarindo (see selected area included in a box, Playa #8, #9, #10, #11, # 12) (1964 to 2005). An intermittent beach (Playa # 12) is located southward from landfill site. Map designed and prepared by Rodríguez, Cielomar, 2006.

Permanent Beach Plain

A permanent beach plain was identified eastward from Punta Tamarindo from 1964 to 2004. This beach showed changes in the subaerial plain extension during these periods (see figure below). An increase in beach plain was measured from 1964 to 1996. Major erosion was observed in 2004 (see figure below). The beach is located to the east side of landfill site. Beach changes may be related to an increase in storm occurrence in the area, and possibly with lack of sediment and/or decrease in biogenic sediment production in the nearshore area. Biogenic sediment production can be reduced by storm effect, sediment runoff from land, man-made activities as land cover changes caused by landfill activities.



Historical beach changes (permanent beach-Playa # 4)) identified eastward from Punta Tamarindo. Graph designed and prepared by Rodríguez, Cielomar, 2005, unpublished undergraduate thesis.



Permanent beach delineation located eastward from Punta Tamarindo (1964 to 2005). Landfill site is located in the box area northward Punta Tamarindo. Map designed and prepared by Rodríguez, Cielomar, 2005.

Historical subaerial reef structure Changes (1964 to 2005)

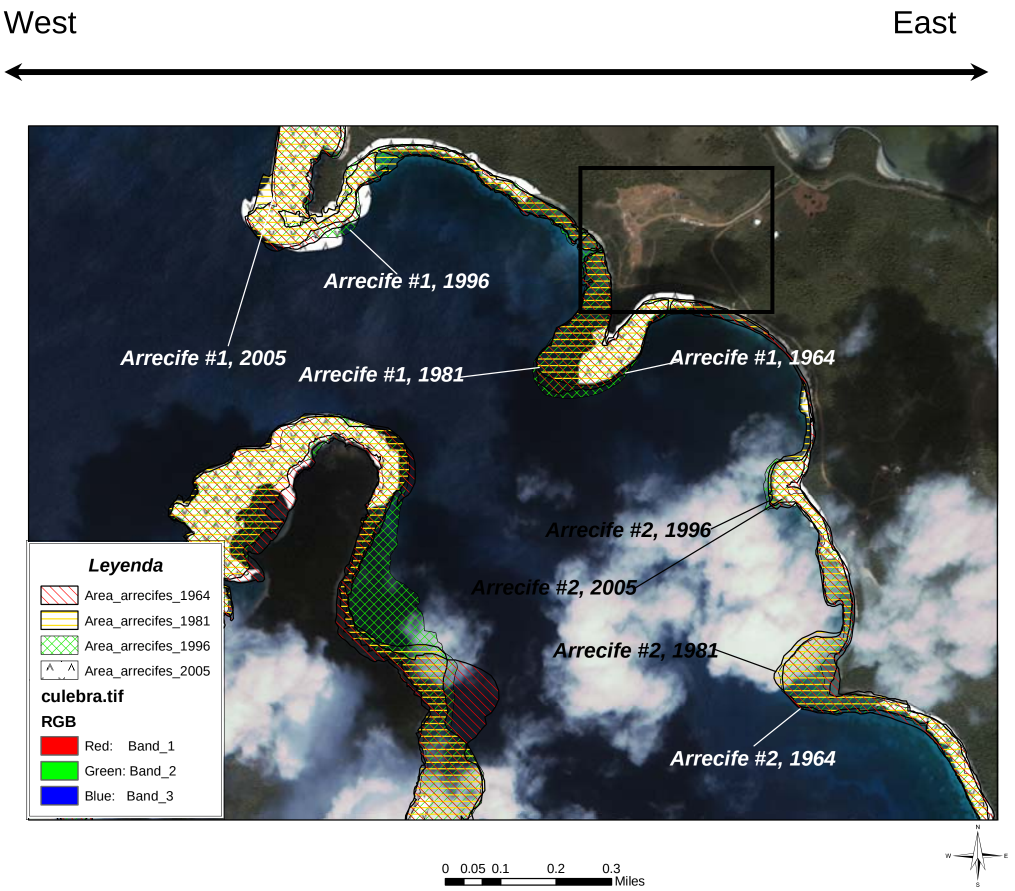
Subaerial reefs structures were identified using vertical aerial photographs for 1964, 1981, 1996 and 2005 period. In this study, the subaerial reef structure was identified using aerial photograph with 1 to 5 meters of spatial resolution. Reef structure distinguished in an aerial photo may be related with fringing coral reef[1], eolianite and/or rock reef. Rock reefs are submerged hard substrate features with low coral cover. Reef structure changes evaluation was done using a map designed and prepared by Rodríguez, 2006[2] that showed changes in subaerial reef structure cover from 1964 to 2005 (see figures below).

Fringing reef structures were identified from Punta Tamarindo Grande to Punta Tamarindo from 1964 to 1996. Fringing reef located near Punta Tamarindo was not identified in aerial photograph from 2005. Fringing reef may not have been identified in the photo due to high suspended sediment concentration or other suspended material. Others possible reasons may be related with the possible erosion or partial destruction of the subaerial reef structure.

---

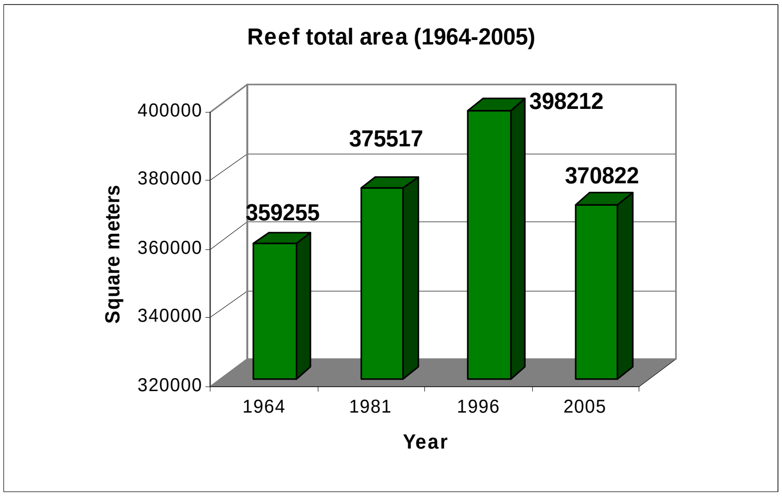
[1] Fringing coral reef occur adjacent to land with little or no separation from the shore (Morelock, web page[1]).

[2] Rodríguez, C., 2006, unpublished undergraduated thesis, UPR, Rio Piedras, mentor, Maritza Barreto



Reef Structure Changes from Punta Tamarindo Grande to Punta Tamarindo, Culebra, Puerto Rico. Map prepared by Rodríguez, Cielomar, 2006. (see landfill site defined in the box)

.



Reef structure total area calculated from polygons defined in aerial photos done by Rodríguez, Cielomar, 2006. Subaerial reef structure area was calculated from Punta Tamarindo Grande to Punta Tamarindo.

Reduction of reef structure in 2005 at Punta Tamarindo near landfill site may be related with high sediment concentration in the nearshore come from land sources that can not permit distinguish reef structure in the east side of Punta Tamarindo.

1964 Aerial Photo

Fringing reef structure was observed continuous from Punta Tamarindo Grande to Punta Tamarindo in 1964 photo.

1981 Aerial Photo

Fringing reef structure was observed continuous from Punta Tamarindo Grande to Punta Tamarindo in 1981 photo.

1996 Aerial Photo

Fringing reef structure was observed continuous from Punta Tamarindo Grande to Punta Tamarindo in 1996 photo.

2005 Aerial Photo

Fringing reef structure is not observed continuous from Punta Tamarindo Grande to Punta Tamarindo. Two main reef patches were observed: a reef structure adjacent to Punta Tamarindo Grande and a reef structure in the eastside from Punta Tamarindo. Reef structure located adjacent to the shoreline near of the landfill area was not found in the 2005 photo. This may be related with the presence of suspended material in the nearshore area that can not permit the visualization of reef structure for this period.

Coastline and Nearshore Geomorphological Characterization (1964, 1981, 1998, 2001 and 2004)

Three main categories are identified in coastline and nearshore sites using multispectral images and panchromatic photos for 1964, 1981, 1996, 2001 and 2004 periods. These categories are: high brightness material, moderate brightness material and low brightness material.

High brightness category (white color) includes a definition of high radiance material as biogenic sand beaches, concrete surface, light color sand and other material. Moderate brightness category (yellow and tan color in the image) includes materials apparently related with soil, sediments from land sources, and/other material transported from land sites. Major land characteristics were defined with these spectral characteristics according studied images. Low brightness category (black color in the image) includes materials with low reflectance as rocks (volcanic rocks as basaltic and beachrock), seagrasses communities and deeper nearshore sites. Qualitative evaluation of 1964, 1981, 1996, 2001 and 2004 images from study sites was conducted to identify possible changes in brightness characterization among images. Quantitative approach can not perform due to differences in sun angle and brightness value format among images.

High Brightness Category (Beach deposits, concrete surface, roads, loss of vegetation cover)

Beach Deposits from Punta Tamarindo Grande to Punta Tamarindo (south from landfill site)

Subaerial beach deposits showed variability in extension from 1964 to 2004 from Punta Tamarindo Grande to Punta Tamarindo. Erosion was mainly observed from 1981 to 2004 at Punta Tamarindo near landfill site. Major morphological changes were identified in this site from 2001 to 2004 period.

1964

Beach plains were easily observed in the area from Punta Tamarindo Grande to Punta Tamarindo. Major sand deposits were observed near Punta Tamarindo and Punta Tamarindo Grande.

1981

Beach plain located near Punta Tamarindo suffered erosion in 1981 period. Major beach deposits were observed to the east of Punta Tamarindo Grande.

1996

Beach plain has erosion at Punta Tamarindo near landfill site. Major beach deposits were observed to the east of Punta Tamarindo Grande.

2001

Erosion was identified in subaerial beaches located to the east and west site at Punta Tamarindo. Major beach deposits were observed near Punta Tamarindo Grande.

2004

Beach plain completelly disappeared on the west of Punta Tamarindo.
A narrow beach appeared in the east of Punta Tamarindo in 2004 period.

Loss of land cover

Loss of land cover was identified at 25 meters elevation contour north from Punta Tamarindo near to landfill site from 1981 to 2001.

Land-sources material and nearshore suspended sediment transport distribution (moderate brightness category)

Results indicated that material from land sources was observed suspended in the longshore path in nearshore areas at Punta Tamarindo from 1964 to 2004. This material was apparently transported down slope from land to nearshore sites. Major land derived material concentration was identified for 2004 period. Higher suspended material concentration (maybe sediments) can affect marine ecosystems as coral reef, seagrass and algae communities producing a decrease in biogenic sediment production in the nearshore area. Minor land-sources material distribution was identified in 1964.

1964

Land sources material was identified in a shoreline spot in the west nearshore side of Punta Tamarindo (see arrow in figures belows). This material was transported down-slope from the 25 meters topographic elevation line to the shoreline for 1964 period. Land-sources material was distributed in a narrow line in the longshore direction to the east of sources area. Suspended material was not transported far away from the shoreline due to the presence of a beach deposit that acts as buffer zone that apparently trapped the transport.. The material is constrained in a narrow longshore path close to the shoreline west side from Punta Tamarindo.

1981

Two main connection of land sources material was identified in shoreline sites (see arrows figure below). These are: a land sources deposits in the shoreline west from Punta Tamarindo and a land source deposit at Punta Tamarindo. Suspended material was mainly observed in nearshore areas at Punta Tamarindo in this period. Suspended sediment was transported to the longshore direction. For this period, suspended sediment showed a more extended transportation to east in the nearshore area.

1996

Three main connections of land sources material were identified in shoreline west and east from Punta Tamarindo near landfill site (see arrows figure below). These are: the two sites already identified in 1981 period westward Punta Tamarindo and Punta Tamarindo. A new land sources material transport site to the shoreline was identified down slope from landfill site. Suspended material was observed in nearshore area for this period. Major material was transported to the east in the longshore direction.

2001

Due to change in spatial and spectral resolution of this image material discrimination can not well be conducted for this period. However, a general assessment of land sources material distribution was done in this section. As well 1996, land sources material was well distributed along shoreline and nearshore site in the west and east sides of Punta Tamarindo. Suspended material concentrations were increased in nearshore sites for this period.

2004

Major suspended sediment was identified in nearshore area in 2004 based in image interpretation (see arrows in figure from 2004). Suspended sediments were transported to the east arriving to Tamarindo Bay. Major extension of suspended sediment in the nearshore may caused by increase of land sediment runoff to the nearshore and loss of the beach plain that acted as a sand trap in the nearshore area.

Rocky deposits, deeper nearshore sides and other low reflectance materials identification in the nearshore area

Nearshore areas showed brightness changes from Punta Tamarindo Grande to Bahía Tamarindo from 1964 to 2004 period. These changes were traduced in: 1) reduction of low reflectance materials in Luis Peña Channel near Punta Tamarindo for 1981 and 1996 2) increase of low reflectance materials in the west site of the Luis Peña Channel for 2001 to 2004. Increase in low reflectance materials can be related with: 1) increase in depths along nearshore sites located to the west side of the Luis Peña Channel and/or 2) loss of benthic sand (biogenic sands) in the nearshore area.

1964

Low brightness category is identified in the center of Luis Peña Channel from Punta Tamarindo Grande to Bahía Tamarindo for 1964. Major biogenic sand (high reflectance) was distributed near shoreline areas from Punta Tamarindo Grande to Punta Tamarindo.

1981

A mixed benthic sediment environment was identified for this period. Biogenic sands were mainly observed at the west side Punta Tamarindo (see figure below from 1981).

1996

Increase in high reflectance material was identified in the nearshore area at Luis Peña Channel for 1996. Biogenic sediments deposits is distributed from Punta Tamarindo Grande to near Punta Tamarindo.

2001 and 2004

Low reflectance materials were identified in Luis Peña Channel nearshore area from Punta Tamarindo Grande to Punta Tamarindo for 2001 and 2004 period (see figures bellows 2001 and 2004). Increase in low reflectance materials may be related with loss of biogenic sand in the nearshore area, increase in suspended sediment in the nearshore areas, increase in depth contourn in the nearshore area and/or increase in rocky area exposition due to loss of benthic sands.

CONCLUSIONS

1. Landfill site showed morphological changes from 1981 to 2004.
    a. An increase in landfill area was identified from 1981 to 2001.
    b. A new barren land was identified to the south from the original landfill site for 1998.
    c. Barren land is still appeared to the south and southeast from the original landfill site for 2001.
    d. A reduction in landfill area was identified from 2001 to 2004.
2. Beach erosion was found in subaerial plains located near Punta Tamarindo from 1981 to 2004.
3. Major beach erosion was measured in coastal site near landfill site for 2004 period.
4. Beach erosion may relate with storm occurrences in the area and landfill activities. Modification in landfill site may produced changes in land cover producing sediment runoff from landfill site to the shoreline near Punta Tamarindo.
5. Land cover changes produced by man-made activities may cause an increase in sediment runoff to the nearshore area. Suspended sediment transported from land sources may cause damage in biogenic sediment sources as coral reef. Biogenic sands are main beach sources in the area.
6. Loss of beach sand produced a major suspended sediment transport to longshore direction for 2001 to 2004 period.
7. A subaerial reef structure was identified in aerial photos from 1964 to 2001. This structure was not observed near Punta Tamarindo (south from landfill area) for 2004 period. Reef Structure can not identify in the photo for this period due to the presence of suspended sediment in the nearshore area and/or erosion in subaerial structure.
8. Biogenic sediment materials are apparently reduced in nearshore bottom areas for 2001 to 2004 period in Luis Peña Channel. Sediment reduction can be related with damage in biogenic sources as coral reef in the nearshore area due to storm events and man-made activities related with landfill site.

REFERENCES

1. Rodríguez, Cielomar, 2005, GEOMORPHOLOGIC CHANGES ASSESSMENT IN THE MARINE RESERVE OF LUIS PENA CANAL, CULEBRA, PUERTO RICO: INTEGRATING REMOTE SENSING, FIELD WORK AND GEOGRAPHIC INFORMATION SYSTEM TECHNIQUES (1964-2005)", unpublished undergraduate thesis, Honor Program, UPR, Río Piedras, advisor: Barreto, M.

Culebra 1964

Culebra 1981

Culebra 1996

Geology of the Municipal Landfill of Culebra

José Seguinot Barbosa, Ph.D.

Department of Environmental Health
Medical Sciences Campus
University of Puerto Rico

Nilda Luhring, M.Sc.

GIS Consultant

Our preliminary analysis concludes that this landfill is located in a volcanic rock formation known as Tks from the upper cretaceous (135 millions years ago) (See geologic map). This formation is composed of volcanic rocks, sandstone, limestone, conglomerate, lava and volcanic tuff. Some marble have been deposit in the marine environment and the rock exposed have been weathered by the ocean and climate. Slope and topography is very steep (more than 15 %) forming good conditions for landslide, weathering and erosion. Although no water bodies were recognized in the area, several runoff channels exist moving in the direction of the coast. The dominant soil type is the Arcilla Daguao (DeE2) (See soil map). This soil has a 20 a 40% eroded capacity and slope. This soil has a very low production capacity, is compose mainly of rock and is develop in arid conditions, where precipitation is less than 10 inches annually. The average temperature of this soil is 79 °F.

Based on the hard conditions of the underground volcanic and sandstone rocks a very low movement of the underground water is expected. On the other hand, this movement increased by the effect of the topography and the incline position of the rock stratification. The anticline formation of the mountain, where the landfill is located, has facilitated the movement toward the east side of the landfill. The eastern aspect of this mountain and the cliff formation in the west direction (where the Luis Peña channel is located) reduced the possible underground lixiviate movement toward the west direction. But this approach will be confirmed after the evaluation of the piezometer water level and after the analysis of the water sample from this site.

Based on the topography map of the site (see topographic map) the average slope is more than 15% near the cliff and mountain slope areas and the medium high of the landfill is about 23 meters. In the central area of the landfill site, where the municipality deposit the garbage, the slope present and average of 5%, with a slow inclination toward the south-east. At least half of the superficial runoff is expected to most toward that direction. The other half probably move toward the west and the north direction. This proved that the natural runoff pattern of this mountain was originally a radial drainage pattern. This means that the probability of water to move into the different direction was almost the same. But the alteration of the natural runoff by the deposit of landfill materials has significantly altered that pattern (see topographic map). This analysis will be more sophisticated develop after the collection of the field topographic and runoff data. After this data collection, a soil loss equation will be applied to confirm the rate of sediment loss in the site.

The focus in this analysis is in the soils, in particular the soil type and its susceptibility for erosion in the study area. For each soil type it was considered the following parameters: slopes, which means the range of inclination of the earth surface; permeability, the capacity of the soil to transfer water in vertical movements; runoff, a depending variable of the permeability; soil depth in base to the bedrock, the deepness of the soil; the depth of the water table, it is used for determine the distance between the soil at a high level in which the soil is saturated; the availability of water, it is used for determine the natural viability for the flora's growth, it can be related to the ability of the soil for agriculture; the shrink-swell potential, used for visualized the behavior of the soil with a change in humidity and establish the stability for a fabricated structure or any that will fabricate.

The parameters more important for the analysis are the slopes, the permeability and the runoff, because there are more related to the susceptibility of a soil for erosion. The variable of slope was defined in classifications in the followings qualitative ranges: leveled slopes, gentle slopes (0-5 %), gentle to moderated slopes (2-5 %), moderated slopes (5-12 %), moderated to steep slopes (12-40%), steep slopes (20-40 %), very steep slopes (40-60 %). For the variable of permeability it was defined by qualitative terms in the followings ranges: low permeability (0.06-0.20 inches/hour), low to moderate permeability (0.20-0.60 inches/hour), moderate permeability

(0.60-2.0 inches/hour), moderate to high permeability (6.0-20.0 inches/hour), high permeability (>20.0 inches/hour).

The soils that comprise the study area are Descalabrado clay loam (DeE2) and Amelia gravelly clay loam (AmC2) from the Amelia Series. The Descalabrado clay loam has a 20 – 40% of slope and is located in the slopes from the sides of the mountains and in the top of the hills of semiarid volcanic soils. In the area are soils from the Guayama Series and rock land. This type of soil (DeE2) has steep slopes, rapid runoff, shallowness from bedrock and has a hazard for erosion. Others characteristic of this soil are: permeability of 0.6-2.0 inches/hour; available water capacity range from 0.10 to 0.15 inches/inches of soil; low corrosivity to the concrete and high corrosivity for uncoated steel; moderated shrink swell potential; it has a depth to seasonal high water table more than 6 feet; the depth of the bedrock is from 1 to 1.5 feet. In short, the DeE2 soil has a steep slope, moderated permeability and a rapid runoff. It should be established the maintenance for fabricated structures made from uncoated steel and the moderated shrink swell potential for the stability of the structures. Therefore, the Descalabrado clay loam soil has a hazard for erosion and is susceptible for erosion. The Amelia gravelly clay loam has a 5 – 12% of slope and is located in the foot slopes in semiarid areas. This soil has the characteristics from the Amelia Series, in which are deep soils, has good drainage and a moderated permeability.

The Amelia gravelly clay loam (AmC2) from the Amelia Series has a 5 - 12% range of slope and is located in the base of the slopes in semiarid areas. This soil has the characteristic of the Amelia Series, in which is established that the soli under this series are deepness, has good drainage and a moderated permeability. Because of the hazard for erosion from de slope percent range, the soil of AmC2 needs soil conservation practices. Others characteristic of this soil are: permeability of 0.6-2.0 inches/hour; available water capacity range from 0.10 to 0.15

inches/inches of soil; moderated corrosivity to the concrete and low corrosivity for uncoated steel; moderated shrink swell potential; it has a depth to seasonal high water table more than 6 feet; the depth of the bedrock is more than 6 feet. In short, the AmC2 soil has a moderate slope and moderated permeability. Therefore, the Amelia gravelly clay loam soil doesn't has the characteristics for susceptibility for erosion, such as steep slopes, low permeability and rapid runoff; it has a hazard for erosion and is susceptible for erosion because of the description of the Amelia Series.

Study of Soil Loss (Universal Soil Loss Equation)

In the process of an analysis based in the sustainable development of a specific area, it should be studied a detailed background of the natural resources, such as soil. One of the factors that should be in consideration for environmental terms is the study of the soil's susceptibility for erosion. The erosion is the process in which the soil is wearied out, in particular the most fertile layers in the soil. Therefore, the erosion is the loss of soil, which means the degradation of this valuable resource. The erosion is classified in two types basing in the cause of origin: antropic erosion, caused by the bad use and management from the humans; and the geologic erosion, caused by the action of the water or the wind. In theory, the soils with the more resistance to the erosion are those with a rock composition, meanwhile the soils with the more vulnerability for erosion are those of a sand or a calcareous composition.

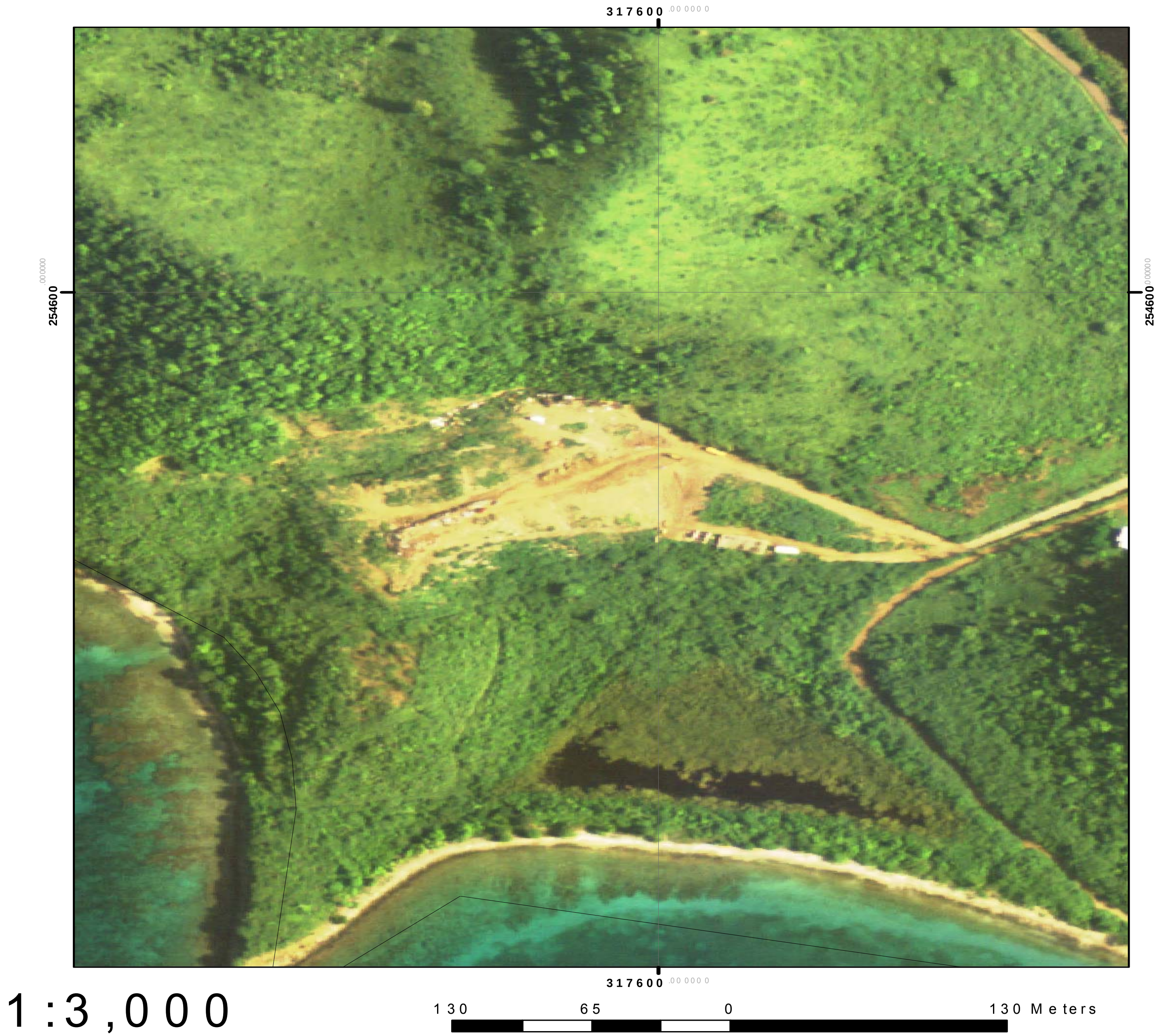
The methodology used for the analysis of soil's susceptibility for erosion is based in two phases. The first phase consist in a general analysis of the soil in function of the "Soil Survey" of the Humacao Region of the U.S. Department of Agriculture. This first phase is useful to bring a perspective of the erosion in general terms. The second phase has the focus in a more detailed study for each soil type in the study area. In this second phase it was used the revised version of the Universal Soil Loss Equation to determine with more precision the areas with more susceptibility for erosion. The Universal Soil Loss Equation are defines by the followings variables: A=RKLSCP, in which A is the annual soil loss, R is the factor for climatic erosion, K is the factor that measure the soil erosion in standard conditions, L is the factor of slope's length, S is the slope factor, C is the land cover and P is the practice for conservation. Each one of the variables mentioned were analyzes for each soil type in the study area.

In the first phase of the analysis using the " Soil Survey", it emphasizes in general terms those soils with susceptibility for erosion. In order to have a more precisely analysis it was used the following revised Universal Soil Loss Equation, A = R K L S C P. The second phase focus in the use of this equation and it shows the following results for the variables:

Soil Type	**R**	**K**	**LS**	**C**	**P**	**A**
AmC2	250	0.24	3.25	0.003	1	0.585
DeE2	250	0.24	8.72	0.003	1	1.570

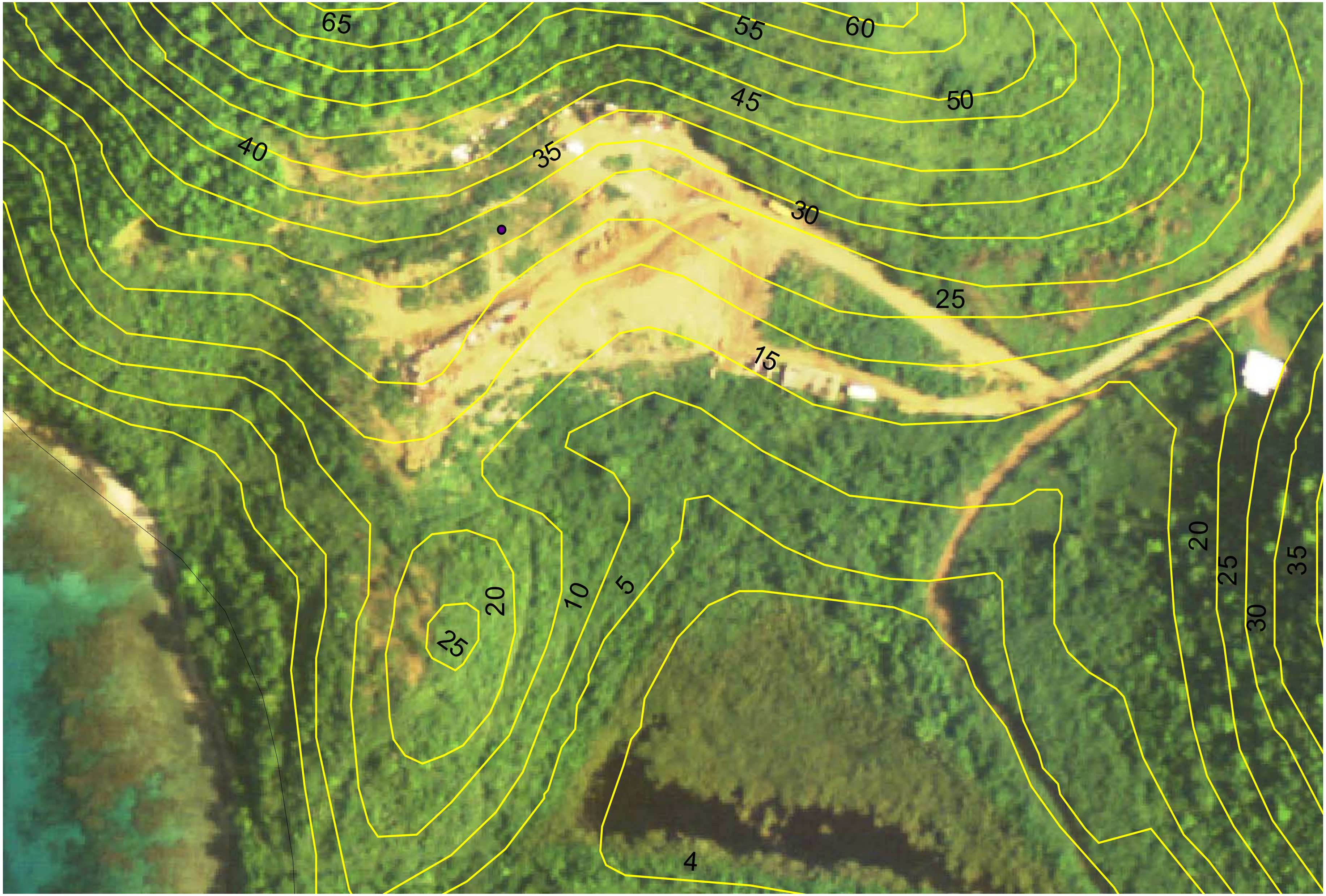
The table shows that the soil type DeE2 has a result more than one (1), and therefore it can be establish the susceptibility for erosion. The soil type AmC2 shows a result less than one (1), therefore it can't be established the susceptibility for erosion, but it is important to state the characteristic of the soil from the Amelia Series, which tends to erode. Basing in this analysis it can be established the determination that the soils that comprise the study area shows susceptibility for erosion.

Vertedero Culebra - Landfill of Culebra



Jose Seguinot Barbosa

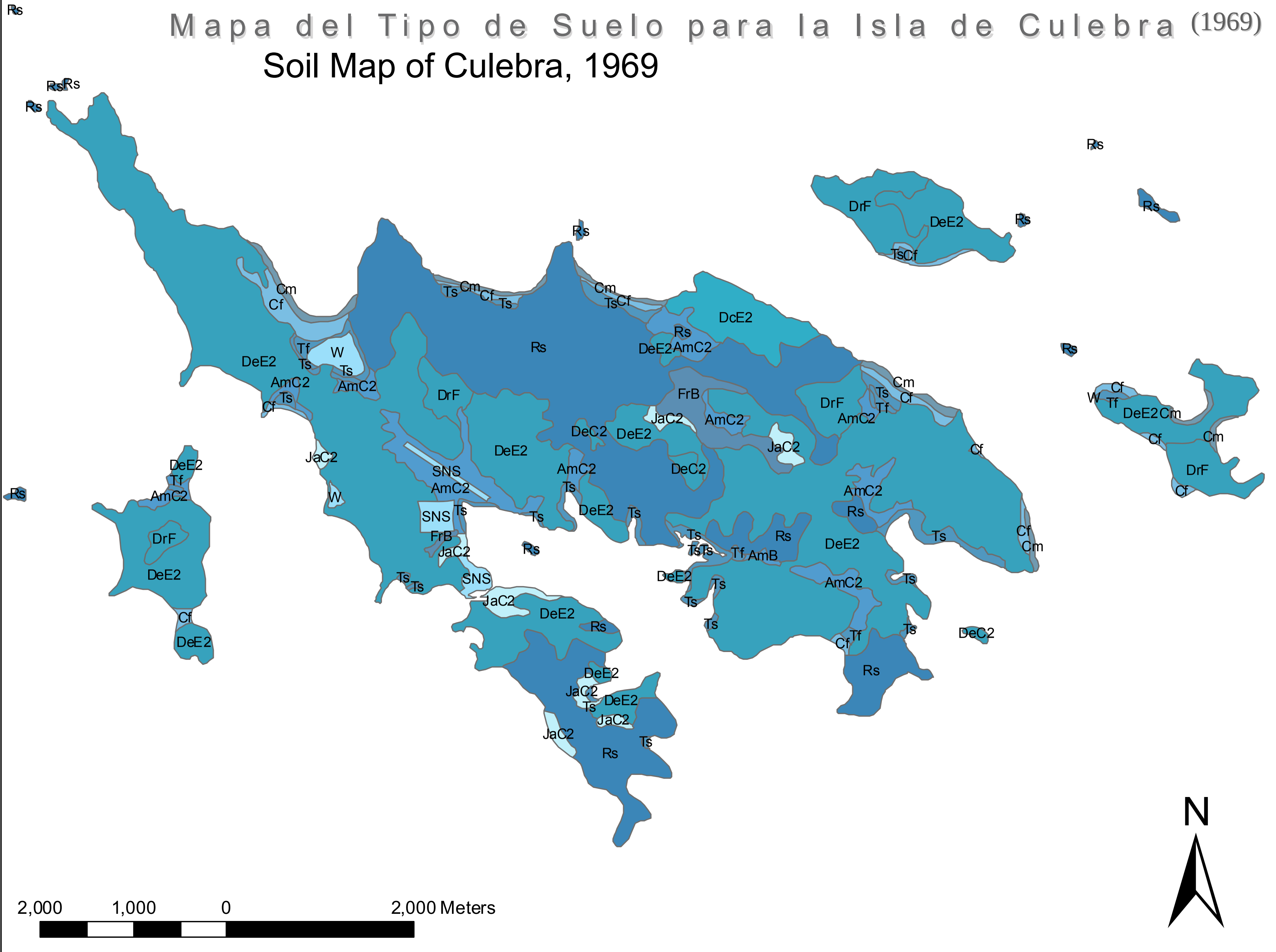
Topography of Culebra landfill



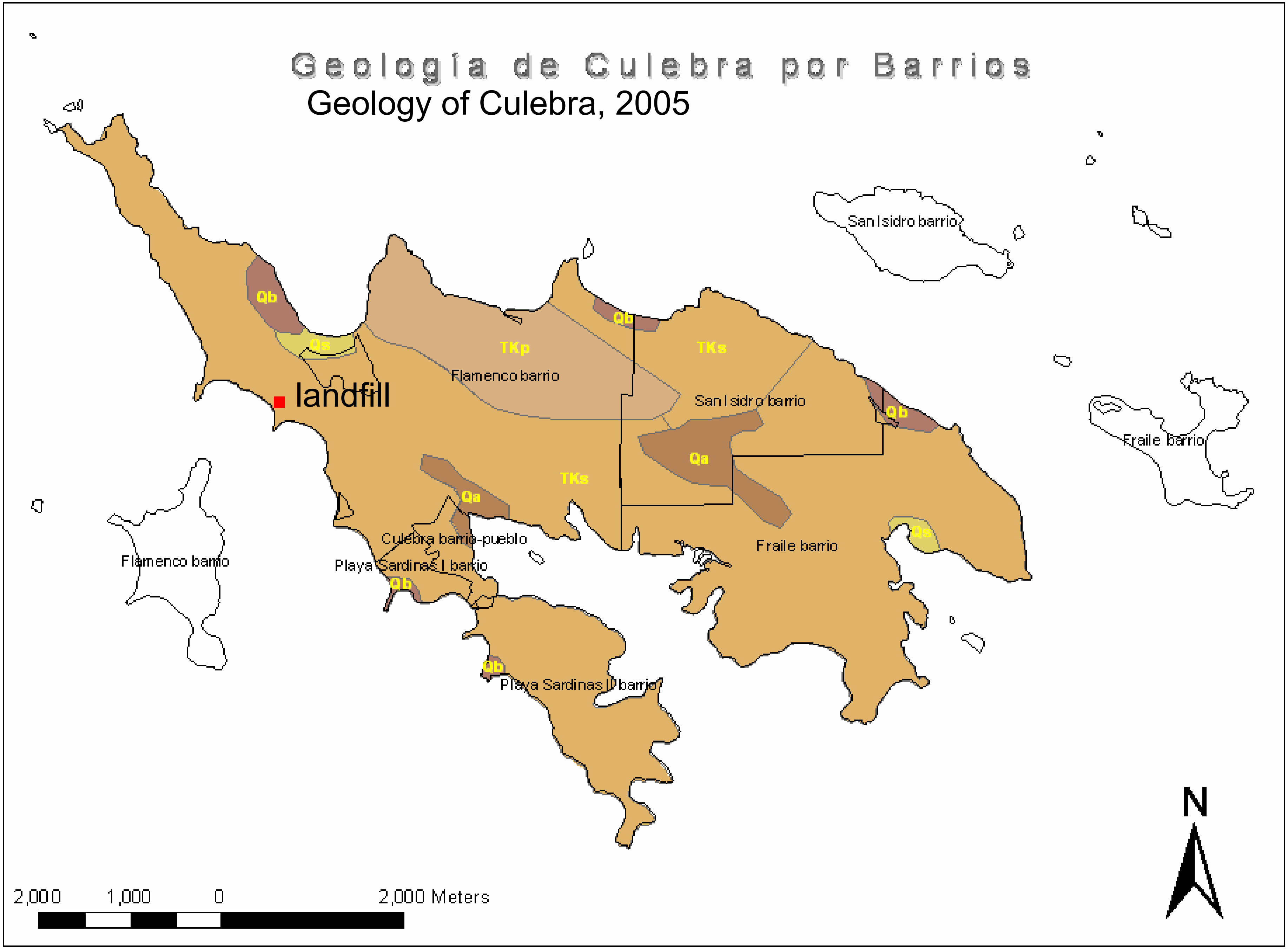
*Elevation in meters

Mapa del Tipo de Suelo para la Isla de Culebra (1969)

Soil Map of Culebra, 1969



Soil Map of Culebra landfill



Geología de Culebra por Barrios

Geology of Culebra, 2005

Biological characterization of coral reef communities adjacent to a municipal landfill, Luis Peña Channel Natural Reserve, Culebra Island, Puerto Rico.

Edwin A. Hernández-Delgado, Ph.D.

Coral Reef Research Group,
Department of Biology,
Río Piedras Campus
University of Puerto Rico,

Summary

1. Coral reef communities adjacent to the Culebra Island municipal landfill were assessed and quantitatively described for the first time to test for any potential landfill operation impact.
2. Given the lack of long-term monitoring, and the resulting temporal and spatial constraints of this study, there were no signs of landfill impacts in adjacent coral reef benthic community structures.
3. Coral reefs adjacent to the landfill still support a high biodiversity.
4. However, reefs are showing signs of unequivocal decline associated to a combination of long-term regional (i.e. sea surface warming, coral bleaching, hurricanes, disease outbreaks) and local factors (i.e., sediment- and nutrient-laden runoff pulses, remote raw sewage impacts).
5. Sediment-laden runoff pulses are often occurring in the landfill after heavy rainfall. Plastic bags and other plastic debris is frequently blown by the wind and ends up at Bahía Tamarindo, but impacts of these were not quantified in this study.
6. There is a need to use coral proxy signals (i.e., annual growth bands, humic acids, heavy metal accumulation) to test for any spatial and/or temporal variation in patterns of impacts.

Introduction

Landfill operations in Culebra Island, Puerto Rico, have been identified as one of the most significant environmental threats to marine communities located within the Luis Peña Channel No-Take Natural Reserve (LPCNR) (Hernández-Delgado, 1994, 2003b, 2004). Most threats are largely associated to highly sediment-laden runoff impacts from the landfill area to adjacent coral reef and seagrass communities. However, such impacts, although documented, have never been quantified. Further, although highly potential, there is no quantitative evidence yet of chemical pollution to nearby seashore, coral reef, seagrass or soft bottom communities as a result of landfill operations. Thus, there is a paramount need to quantify such impacts.

The Culebra Island landfill was established during 1984 in Flamenco Ward at approximately 25 m from the shoreline of Bahía Tamarindo within the LPCNR (Figures 1 and 2). Biological communities within the reserve support an outstanding biodiversity representative of the northeastern Caribbean region (Hernández-Delgado, 2000, 2003; Hernández-Delgado et al., 2000; Hernández-Delgado and Rosado-Matías, 2003). Biological communities located in Bahía Tamarindo and Punta Rompeanzuelo, in close proximity to the landfill, are also highly diverse and highly structured (Hernández-Delgado, 1994, 2003a). However, water quality degradation has been pointed out as one of the causes of coral reef and fish community declines in Culebra (Hernández-Delgado and Sabat, in review; Hernández-Delgado et al., 2006). The Department of Natural and Environmental Resources (DNER) is highly concerned with the potential impacts of the Culebra landfill operations on the local marine communities. But in spite of the ecological, economic, aesthetic and touristic significance of Bahía Tamarindo marine communities, there is no information regarding environmental impacts of landfill operations.

The objective of this part of Phase I report was to produce a biological characterization of coral reef communities adjacent to the Culebra Island landfill, within the LCNR.

Methodology

Study sites.

Studies were conducted at four coral reef locations within the LPCNR (Figure 1). These included: one *impact* site (Punta Rompeanzuelo), and three *control* sites (Arrecife El Banderote, Punta Tamarindo Chico, Cayo Luis Peña-north coast). LPCNR covers an area of approximately 636 ha, with depths reaching approximately 24 m. Patchy macroalgal plains cover approximately 30% of the bottom, closely followed by continuous seagrass communities with 28% (Hernández-Delgado, 2003). Colonized pavements cover nearly 20% of the bottom. Other benthic categories are listed in Table 1.

TABLE 1. Benthic habitat categories within the LPCNR*.

Benthic categories	%
Linear reef	5.59
Colonized bedrock	6.67
Colonized pavement	19.75
Scattered coral rock	0.65
Colonized pavement with channels	3.30
Patch reef	0.86
Seagrass (continuous)	28.36
Seagrass (70-90%)	1.20
Seagrass (50-70%)	0.0
Seagrass (30-50%)	0.78
Patchy macroalgal plain (10-50%)	29.89
Sand	2.95

FIGURE 1. Study sites within LPCNR, Culebra Island. PRA= Punta Rompeanzuelos (impact site); AEB= Arrecife El Banderote (control); PTC= Punta Tamarindo Chico (control); CLPN= Cayo Luis Peña-north (control).

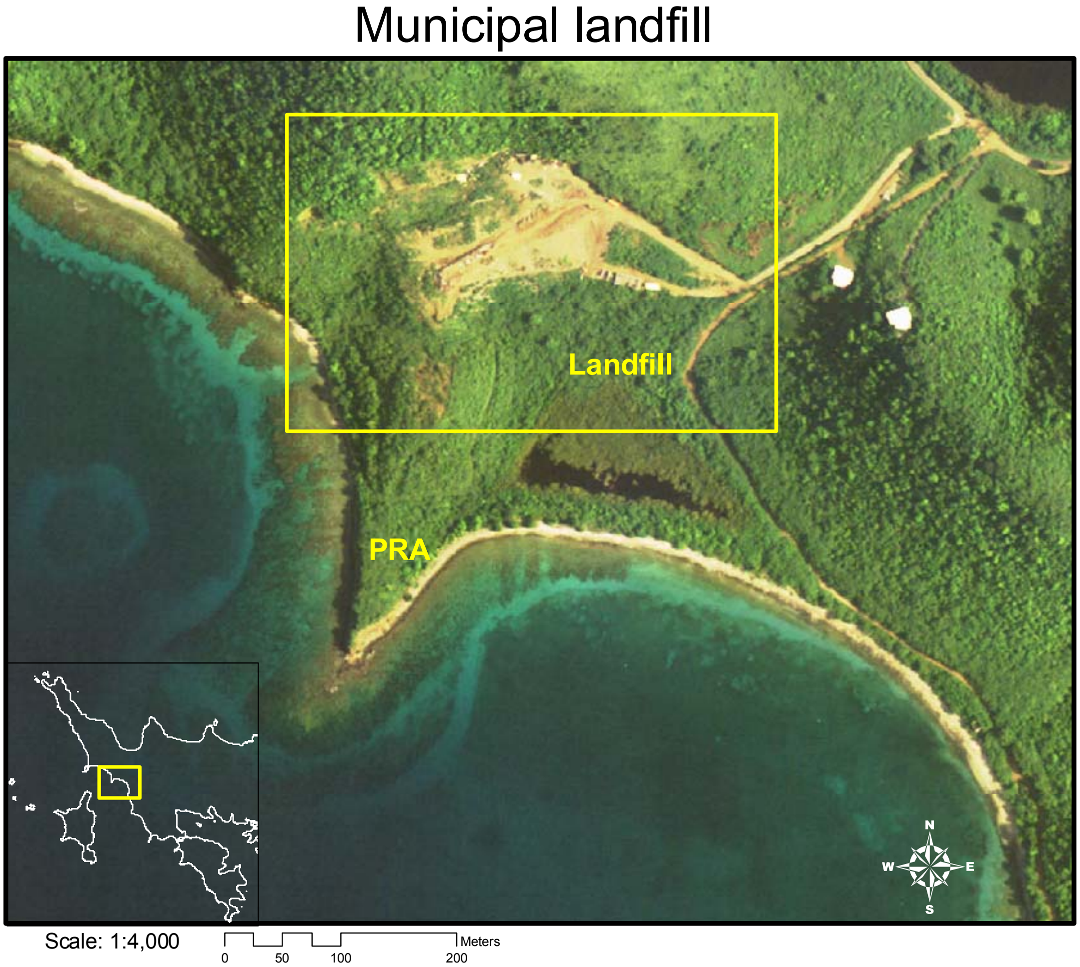

Municipal landfill

FIGURE 2. Detail of Culebra Island municipal landfill and its adjacent marine communities at Punta Rompeanzuelo (PRA). Note the presence of linear reefs, colonized pavements, colonized bedrock, continuous seagrass, sandy bottoms, rocky shores and sandy beaches. Also, note the wetland area between the landfill and the shoreline.

Spatial patterns in coral reef community structure.

Benthic surveys of coral reef communities were carried out to test for any significant spatial pattern in the community structure of coral reefs resulting from potential landfill-based pollution. Briefly, six replicate 30 m-long point-count transects were randomly sampled using digital video imaging at the presumed *impact* site (Punta Rompeanzuelo) and at each one of three *control* sites (Arrecife El Banderote, Punta Tamarindo Chico, Cayo Luis Peña-north coast). This approach provided baseline information regarding the actual condition of coral reefs (i.e., coral species richness, % coral cover, % algal cover (functional groups: macroalgae, filamentous algae, *Halimeda*, crustose coralline algae), % sponge cover, % zoanthid cover, % cyanobacterial cover, and other components, coral species diversity index, coral species evenness). Corals were also assessed for any disease, syndrome, bleaching or other adverse vitality conditions. Whenever possible, sources of recent mortality were identified. Possibilities included sediment deposition, storm damage, parrotfish bites, damselfish bites and/or algal gardens, predation on the soft tissues by snails like *Coralliophila abbreviata* or the bristle worm *Hermodice carunculata*, various effects of adjacent benthic algae, and any other spatial competitors (e.g., *Erythropodium caribaeorum*, other stony corals).

Differences among sites were tested with a one way analysis of variance (ANOVA) and/or Kruskal-Wallis non-parametric ANOVA where indicated. Changes in community structure were tested by means of multivariate statistical tests. Community matrices were compiled and imported into PRIMER ecological statistics software package for multivariate analysis (Clarke and Warwick, 2001). Mean data from each site were classified with hierarchical clustering using the Bray-Curtis group average linkage method (Bray and Curtis, 1957) and then ordinated using a non-metric multidimensional scaling plot. Spatial variation patterns were tested using PRIMER's multivariate equivalent of an ANOVA called ANOSIM. Key taxa responsible for spatial variation in community structure between sites were determined using the SIMPER routine.

Results

Qualitative description of benthic communities adjacent to the Culebra Island landfill.

The following section is largely based on Hernández-Delgado (2003), although updated information is provided.

Bahía Tamarindo-North (BTN): This zone extends from Punta Tamarindo Chico down to Punta Rompeanzuelo (Figures 1, 3, 4). It covers an approximate area of 32.55 ha, and extends from the shoreline to depths of approximately 20 m. Predominant benthic habitats include continuous seagrass communities, colonized bedrock, and linear reefs bordered by sandy bottoms. A total of 47 coral species have been identified, including 14 octocorals, 4 hydrocorals, and 29 scleractinians. Its shallow reefs support a relatively low % coral cover (<20%), and constitute important nursery grounds for a myriad of reef fish and invertebrate species, while their seagrass communities constitute a nursery ground for Queen Conch, *Strombus gigas*. They are also part of the designated critical habitat for endangered green turtle, *Chelonia mydas*.

Punta Rompeanzuelo (PRA): Most of this zone (Figures 1, 5-7) is componed by a shallow (0-7 m) coralline community with a combination of colonized bedrock and linear reef, with limited % coral cover (<15%). However, its shallow grounds right in front of the rocky headland support an

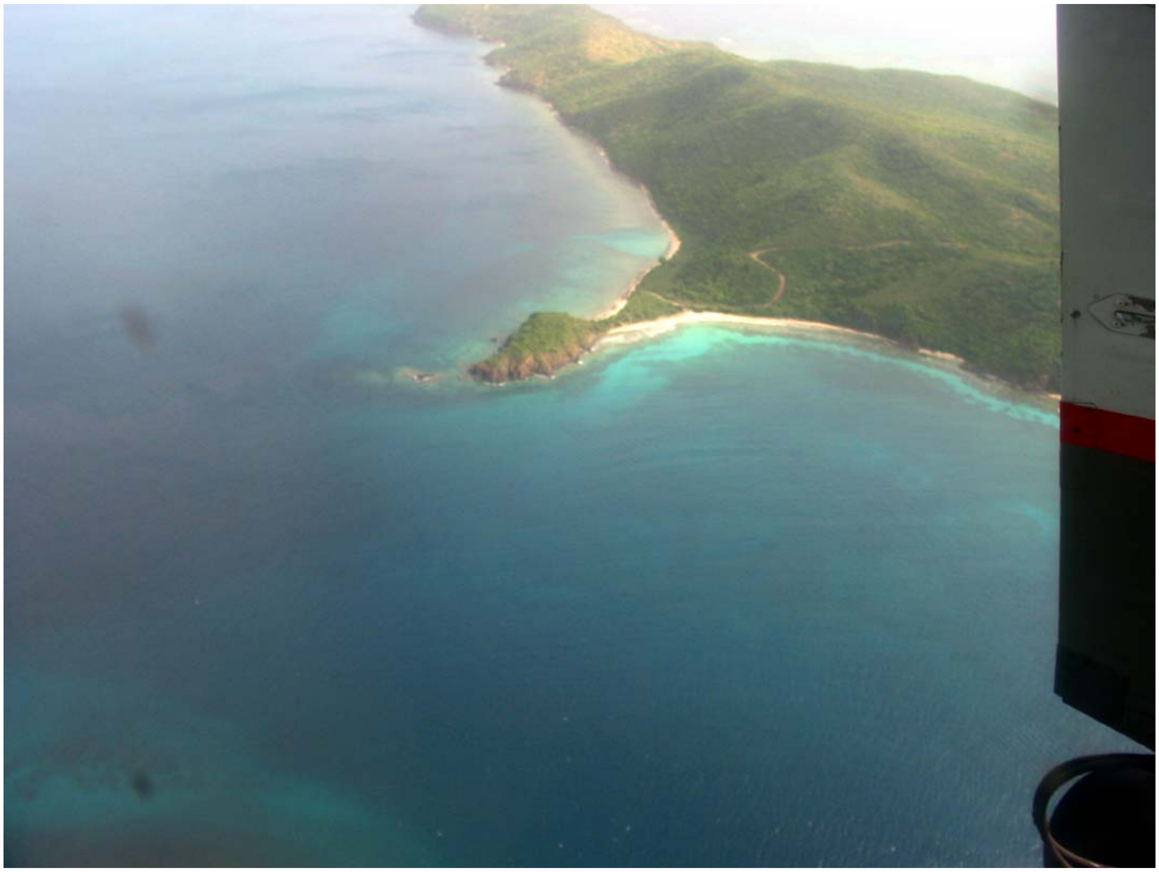


FIGURE 3. Bahía Tamarindo (north) at the right side of the figure, with a view of Luis Peña Channel, Punta Tamarindo Chico and Península Flamenco.

FIGURE 4. Marine communities of Bahía Tamarindo (north). From top left: A) Seagrass community with high dominance exerted by turtle grass, *Thalassia testudinum* (5 m); B) Juvenile Queen Conch, *Strombus gigas*, in a patch dominated by manatee grass, *Syringodium filiforme* (5 m); C) Partial view of a marginal reef (2.5 m); D) Sponge *Callyspongia vaginalis* showing a turtle bite (4 m); E) Fire coral, *Millepora complanata*, is dominant at shallow reefs (2 m); and F) Sandy bottom fringe (3 m).

extensive population of zoanthid *Palythoa caribbaeorum*, with % cover exceeding 80% in some areas. There is also a high abundance of juvenile corals, including elkhorn coral (*Acropora palmata*), brain corals (*Diploria strigosa*, *D. clivosa*), as well as mustard hill coral (*Porites astreoides*), finger coral (*P. porites*), starlet coral (*Siderastrea radians*), golfball coral (*Favia fragum*), and fire coral (*Millepora complanata*). This reef also supports an abundant community of juvenile reef fishes and occasional large piscivorous fishes. PRA and BTN constitute the two closest coral reef communities to the Culebra Island municipal landfill. Colonized bedrock and linear reefs end up in a sandy bottom fringe that separates them from continuous seagrasses. Deeper habitats (15-20 m) are characterized by a combination of sandy or low-density seagrass bottoms, intermingled with colonized pavements and algal plains.

Bahía Tamarindo-South (BTS): This zone extends from Punta Rompeanzuelo south to Punta Tamarindo Chico (Figures 1, 8-10), and reach depths of 12 to 18 m. Predominant benthic habitats include continuous seagrasses, colonized bedrock, sandy bottoms, and limited linear reefs. A total of 42 coral species have been documented, including 11 octocorals, 3 hydrocorals, and 28 scleractinians. There are usually high Queen Conch (*Strombus gigas*) densities, as well as a resident population of endangered green turtle (*Chelonia mydas*). These seagrasses were designated as critical habitat for this species. The narrow shallow fringing reef system (<2 m), and Arrecife El Banderote (< 4 m) function as a critical nursery ground of a large amount of fish species, including many that are commercially important, such as snappers (*Lutjanus analis*, *L. griseus*, *L. mahogoni*, *Ocyurus chrysurus*), grunts (*Haemulon* spp.), groupers (*Epinephelus striatus*, *E. guttatus*, *E. ascencions*, *Cephalopholis fulva*), and parrotfishes (Scaridae spp.).

FIGURE 5. Bahía Tamarindo, northern (left) and southern segments (right). Punta Rompeanzuelo is located right in the center of the image, with Culebra Island landfill in the background. Note dirt trails and roads accessing the coast from the landfill (western face). Also, note wetland between the landfill and the shoreline in its southern face.

FIGURE 6. Marine communities of Punta Rompeanzuelo. From top left: A) Colonized bedrock (1.5 m); B) Elkhorn coral colonies (*Acropora palmata*) (1.5 m); C) Juvenile grunts (*Haemulon* spp.) and yellowtail snapper (*Ocyurus chrysurus*) (3 m); D) Tomtate school (*Haemulon aurolineatum*) (4 m); E) Stoplight parrotfish (*Sparisoma viride*) (3 m); and F) High density of coral recruits on colonized bedrock (2 m).

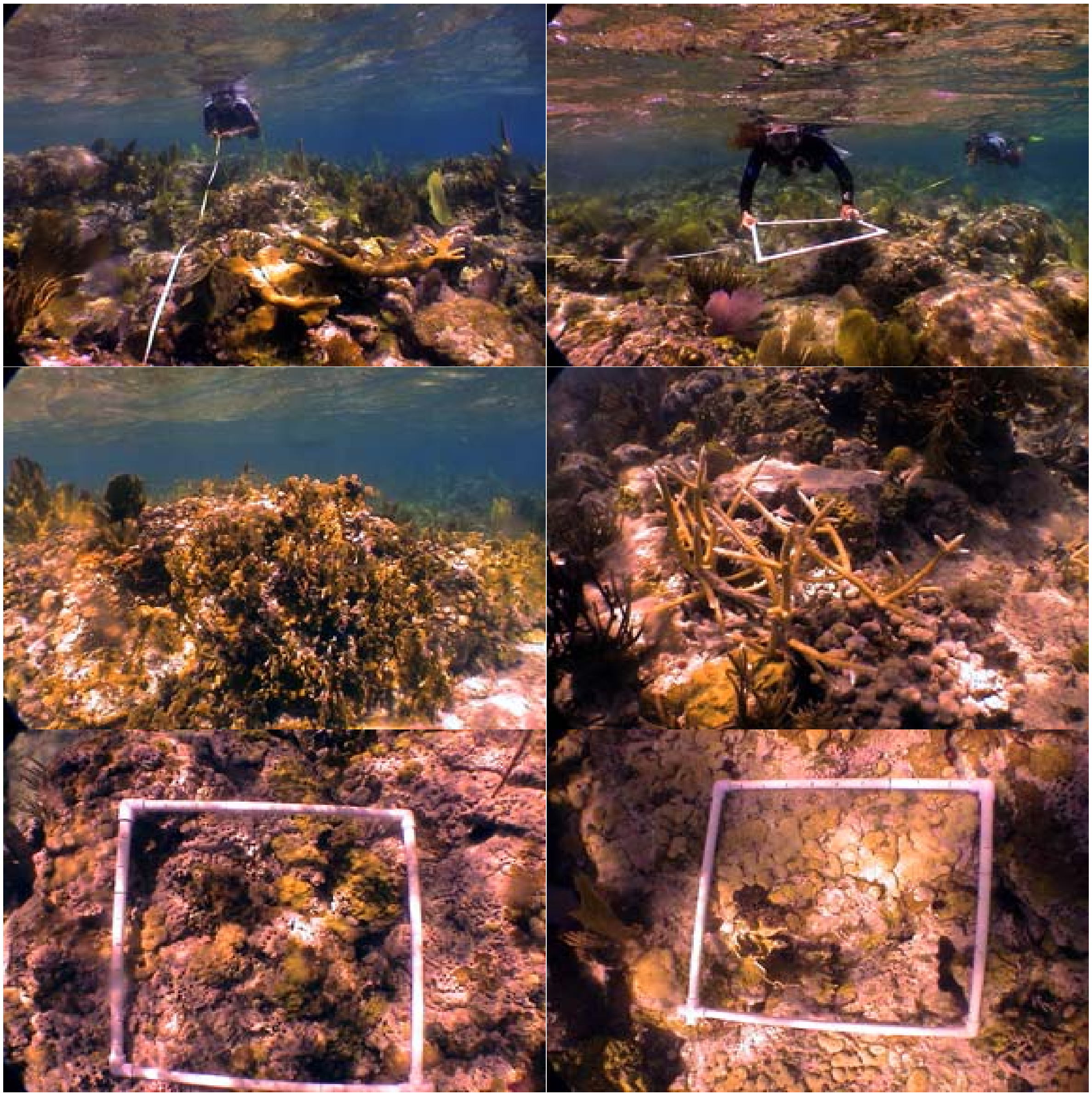


FIGURE 7. Marine communities of Punta Rompeanzuelo. From top left: A) and B) Volunteer divers laying transect lines (1.5 m), note presence of juvenile threatened elkhorn coral (*Acropora palmata*) and abundant seafans (*Gorgonia* spp.); C) Abundant fire coral (*Millepora complanata*) and zoanthid (*Palythoa caribbaorum*) (0.75 m); D) Small colony of threatened staghorn coral (*Acropora cervicornis*); D and E) Examples of highly abundant juvenile corals and zoanthids.

FIGURE 8. Arrecife El Banderote, Bahía Tamarindo (south).

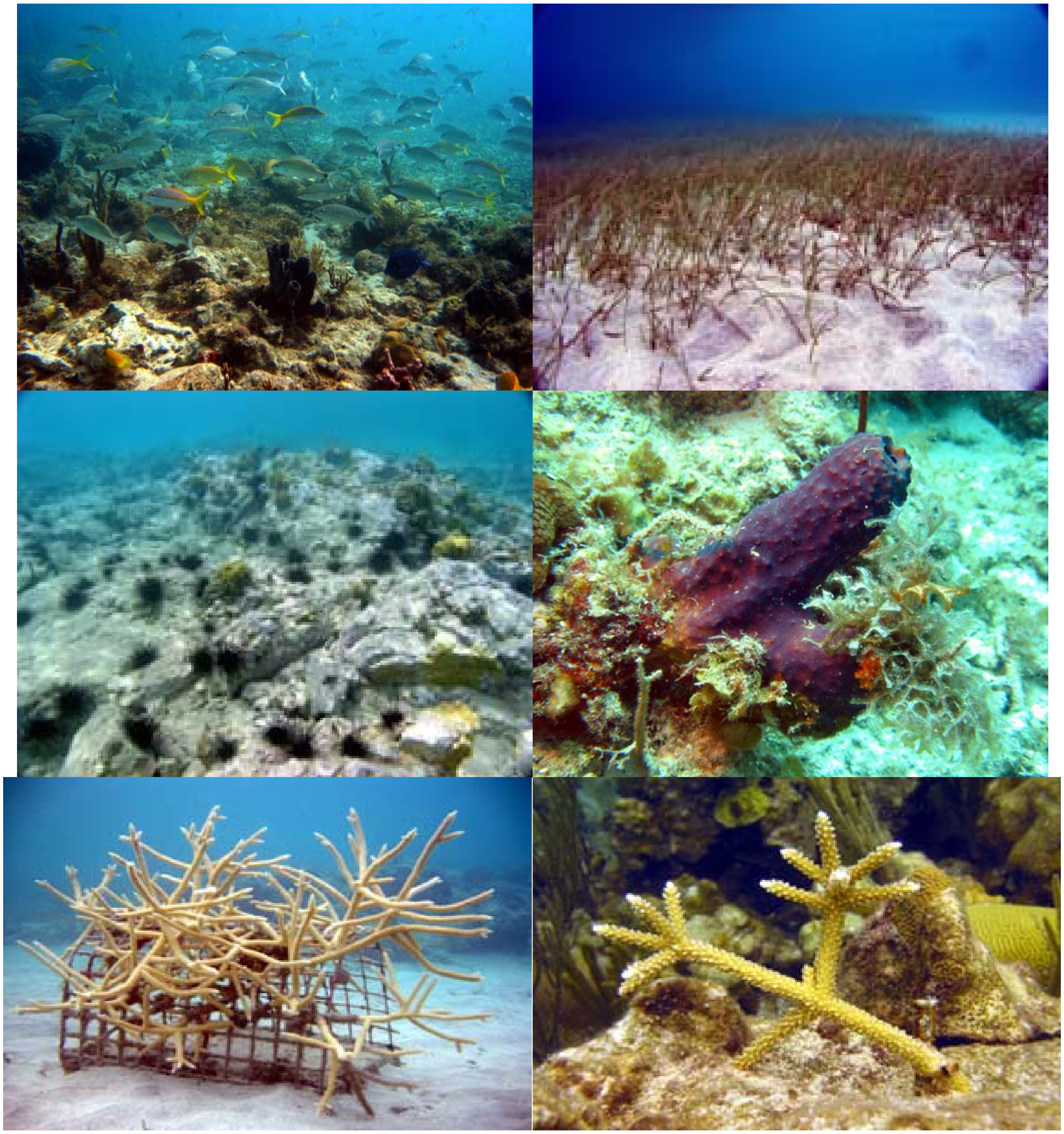


FIGURE 9. Marine communities of Arrecife El Banderote. From top left: A) Juvenile grunts (*Haemulon* spp.), mutton snapper (*Lutjanus analis*), mahogany snapper (*L. mahogoni*), and yellowtail snapper (*Ocyurus chrysurus*) (4 m); B) Manatee grass (*Syringodium filiforme*) (5 m); C) Dense aggregation of long-spine sea urchin (*Diadema antillarum*) (2 m); D) Purple variety of branching sponge (*Pseudoceratina crassa*) (4 m); E) Staghorn coral (*Acropora cervicornis*) farming unit (3.5 m); and F) Harvested fragment of staghorn coral recently transplanted to the coral reef as part of an experimental restocking effort on formerly bombarded coral reefs.

Arrecife El Banderote also supports a highly abundant juvenile coral population, as well as a surviving population of elkhorn coral (*Acropora palmate*), and a recovering population of staghorn coral (*A. cervicornis*). There is also a current staghorn coral farming and restocking project conducted by the University of Puerto Rico's Coral Reef Research Group, in collaboration with NGOs Sociedad Ambiente Marino, Coralations, and the Culebra Island Fishers Association. El Banderote also supports an impressive dense population of the long-spine sea urchin (*Diadema antillarum*).

Punta Tamarindo Chico (PTC): This area separates Bahía Tamarindo from Bahía Tarja (Figure 1, 10, 11). Depths range from the shoreline down to approximately 12 m, with predominant habitats that include colonized bedrock, continuous seagrasses and sandy bottoms. A total of 58 coral species have been documented at PTC, including 16 octocorals, 4 hydrocorals, and 38 scleractinians. PTC shares a lot of characteristics with previously described locations, with the difference that it sustains a higher habitat heterogeneity, thus supporting high density juvenile coral stands, as well as high fish densities.

Cayo Luis Peña-northern coast (CLPN): This area is largely composed of colonized pavements, often with channels, and colonized bedrock (Figures 1, 12-15). These habitats function as a hard ground dominated by soft corals and sponges. There is also a small linear reef, dominated by massive star corals, *Montastraea annularis*, as well as some isolated patches of elkhorn coral, *Acropora palmata*, surrounded by sand bottoms. Depths range from shoreline to approximately 18 m. A total of 63 coral species have been identified at CLPN, including 27 octocorals, 3 hydrocorals, and 33 scleractinians.

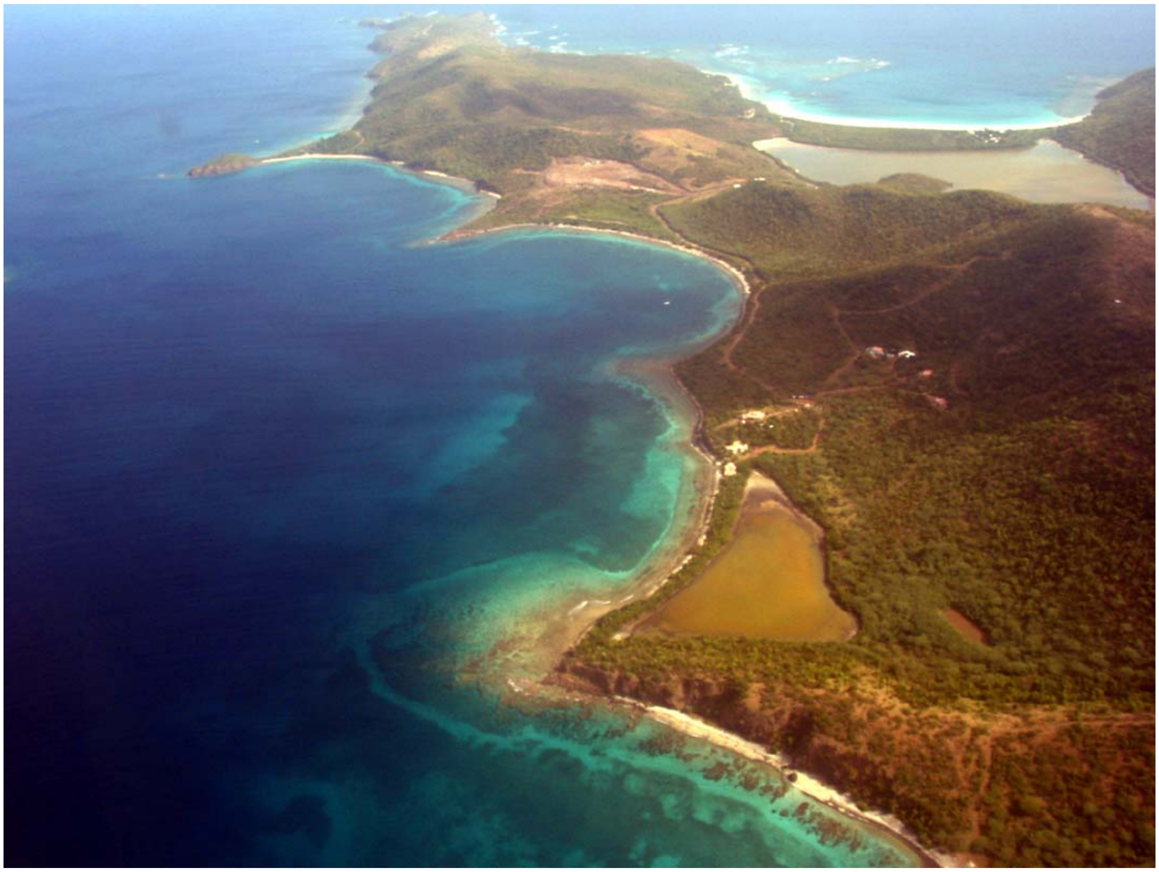


FIGURE 10. Eastern margin of LPCNR. From south to north: Bahía Tarja, Punta Tamarindo Chico (with Laguna Cornelio), Bahía Tamarindo, Arrecife El Banderote, Punta Rompeanzuelos, Punta Tamarindo Grande, and Península Flamenco. Note Flamenco Lagoon and Flamenco Bay in top right.

FIGURE 11. Marine communities of Punta Tamarindo Chico. From top left: A) French angelfish (*Pomacanthus paru*) at a colonized pavement (8m); B) Barracuda (*Sphyraena barracuda*) (9m); C) Detail of typical benthic community at a colonized bedrock (6 m); D) Spanish hogfish (*Lachnolaimus maximus*) (7 m); E) Mixed bottom of colonized pavements, sparse rocks, rubble and sand bottoms (5 m); and F) Continuous turtle grass (*Thalassia testudinum*) (8 m).

FIGURE 12. Punta Vapor, Cayo Luis Peña-northwest.

FIGURE 13. Northern coast of Cayo Luis Peña, including Punta Rociada.

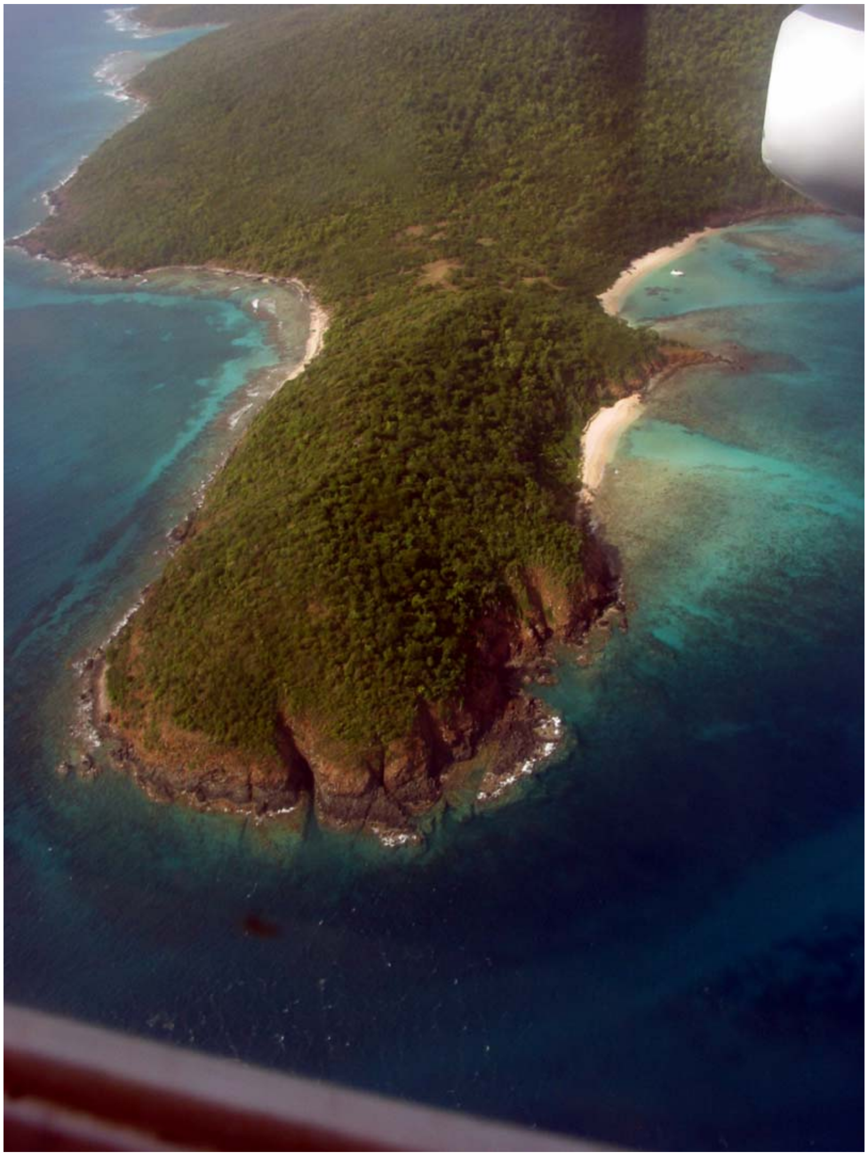


FIGURE 14. Punta Prieta, Cayo Luis Peña-northeast.

FIGURE 15. Marine communities of Cayo Luis Peña-north. From top left: A) Coralline community at a colonized rocky shore (1.5 m); B) Sponge (*Verongula rigida*) is one of the abundant sponge species at colonized pavements (5 m); C) Partial view of a colonized pavement (6 m); D) Detail of sponge *Callyspongia vaginalis*, close to octocoral *Plexaurella nutans*, and a colony of the blue bell tunicate *Clavelina puerto-secensis* at a colonized pavement with channels (8 m).

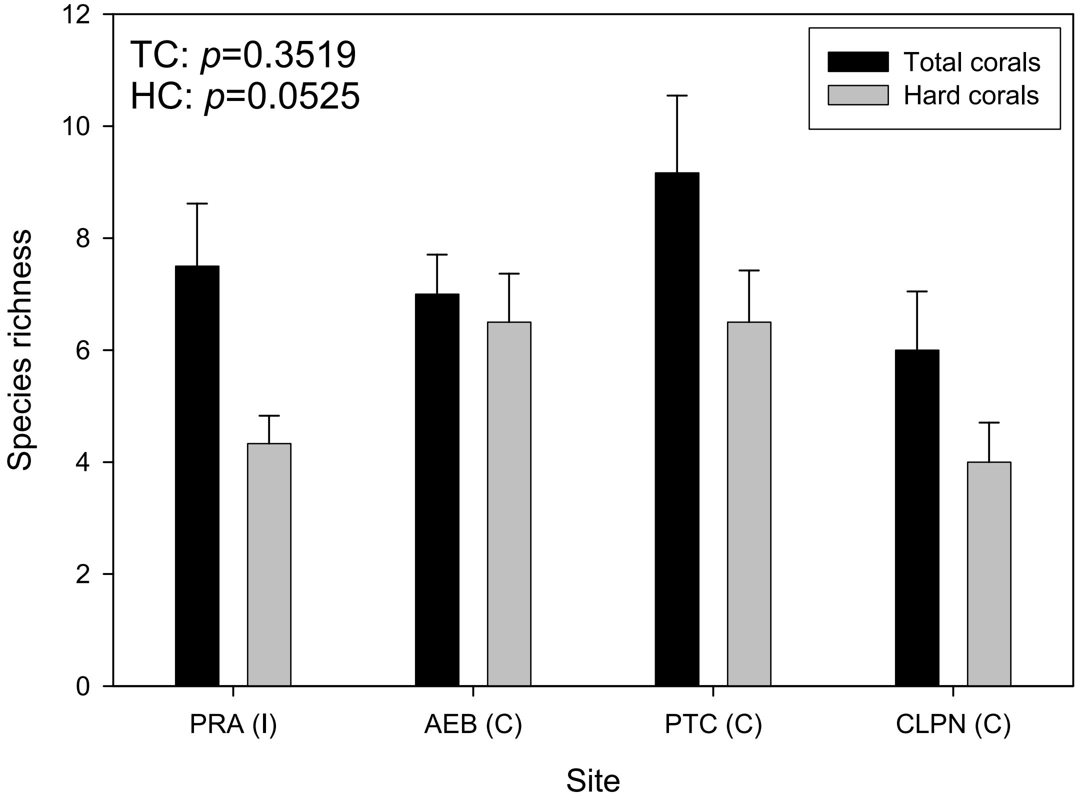


FIGURE 16. Species richness (total and hard corals). I= impacted reef; C=control reef.

Quantitative characterization of coral reef communities.

The highest mean total coral species richness was documented at PTC (9.2), with lower values at CLPN (6.0) (Figure 16). The highest mean hard coral species richness was documented at AEB and PTC (6.5), with lower values at CLPN (4.3), although none of these differences were significant. Total colony abundance was highest at the impact site in PRA (23.3), with a lowest value at CLPN (10.4) (Figure 17). However, that difference was not significant due to the high variance associated to high coral patchiness at PRA. But, hard coral colony abundance resulted significantly higher with 14.3 at AEB (p=0.0317).

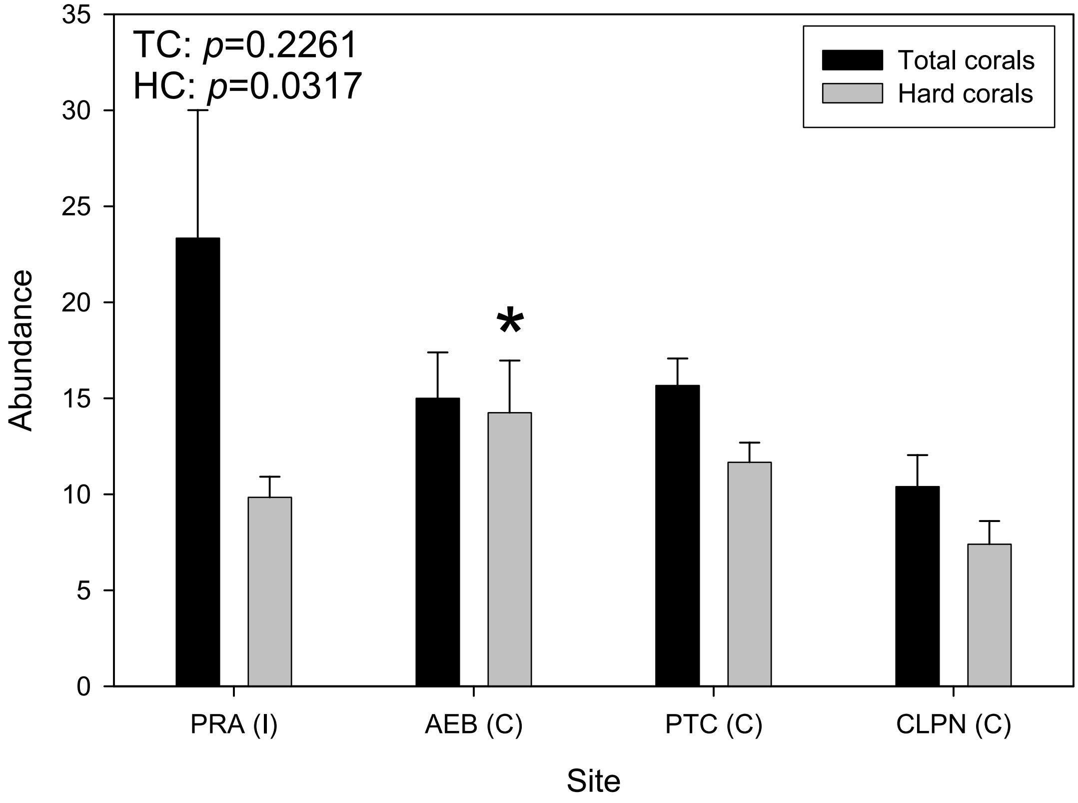


FIGURE 17. Colony abundance (total and hard corals). I= impacted reef; C=control reef.

Although % coral cover averaged 38.5% at the surveyed areas of PRA, with lowest values at CLPN (17%), this difference was not significant due to high between-transect variation (Figure 18). The highest frequency of scleractinian corals (74%) and hydrocorals (22%) was documented at AEB, with the highest frequency of octocorals (42%) occurring at the impact site in PRA (Figure 19). However, differences among sites were not significant for any of the coral groups.

Percent partial colony mortality was not significant among sites (Figure 20), but percent recent colony mortality was significantly higher (*p*=0.0354) at AEB (8.5%) and the impacted site at

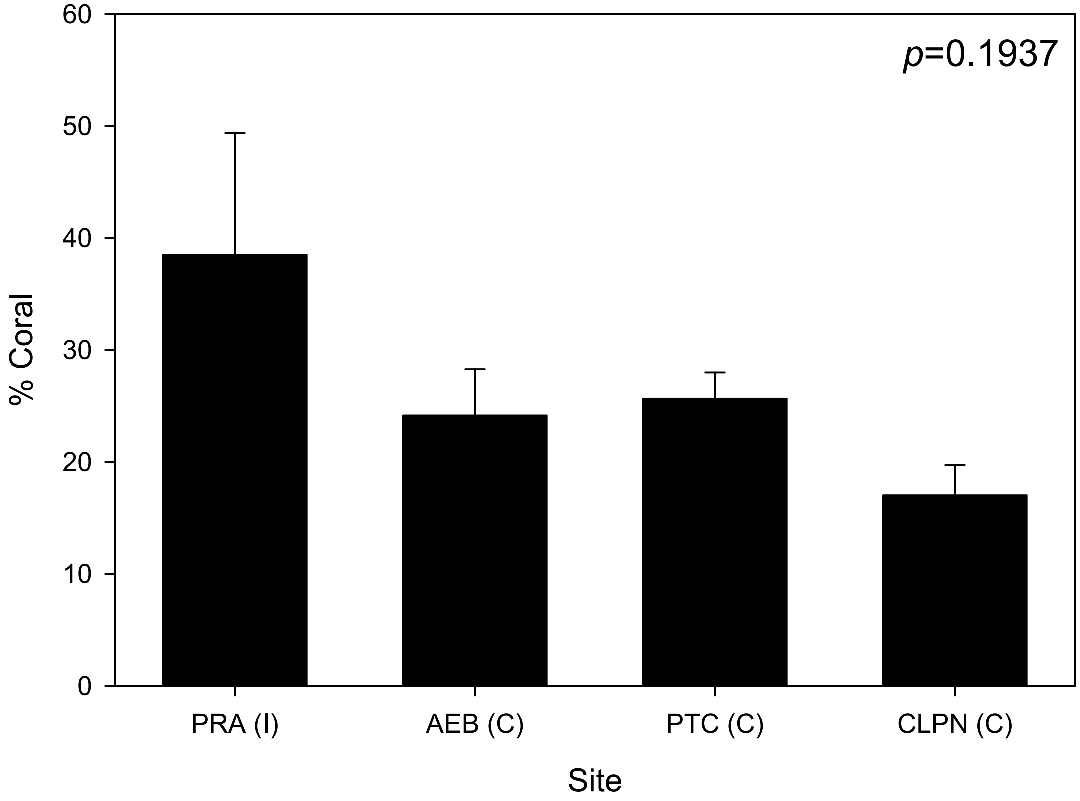


FIGURE 18. Percent living coral cover. I= impacted reef; C=control reef.

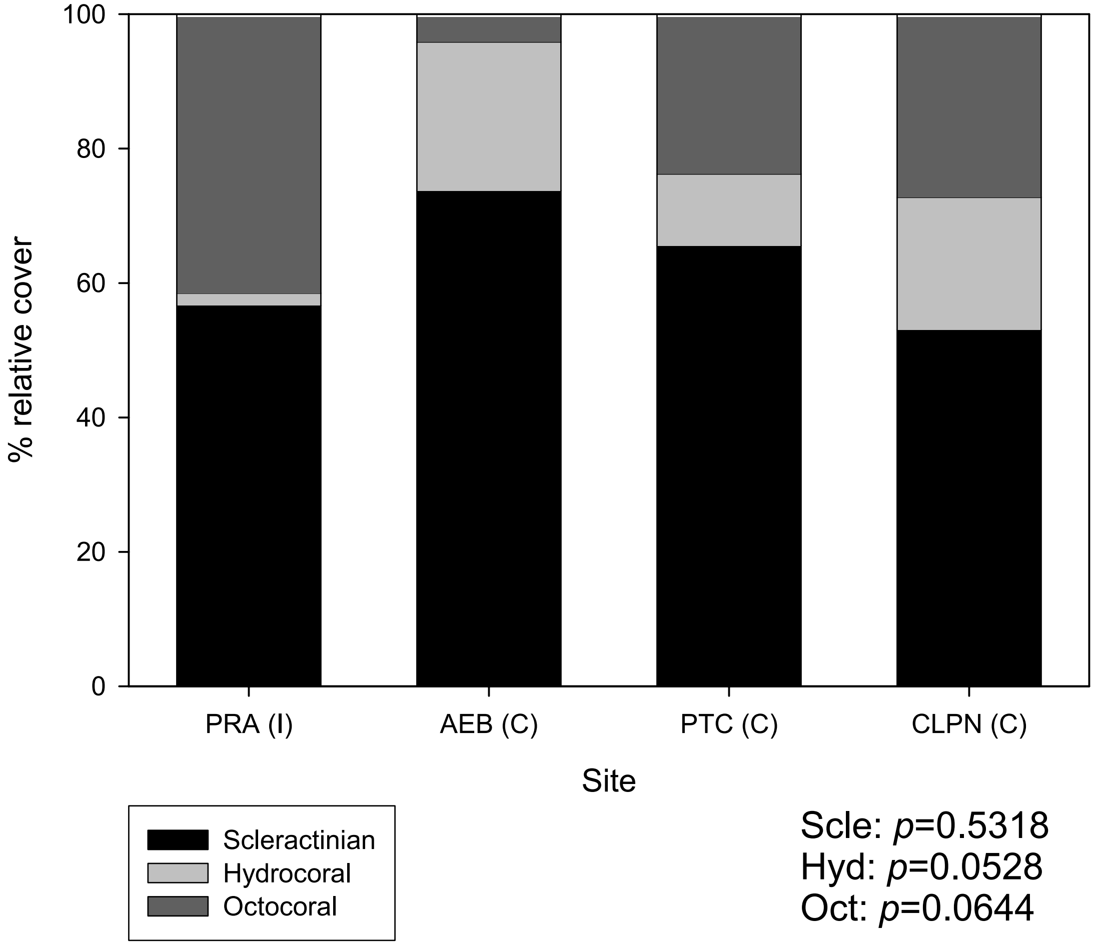


FIGURE 19. Percent relative coral cover. I= impacted reef; C=control reef.

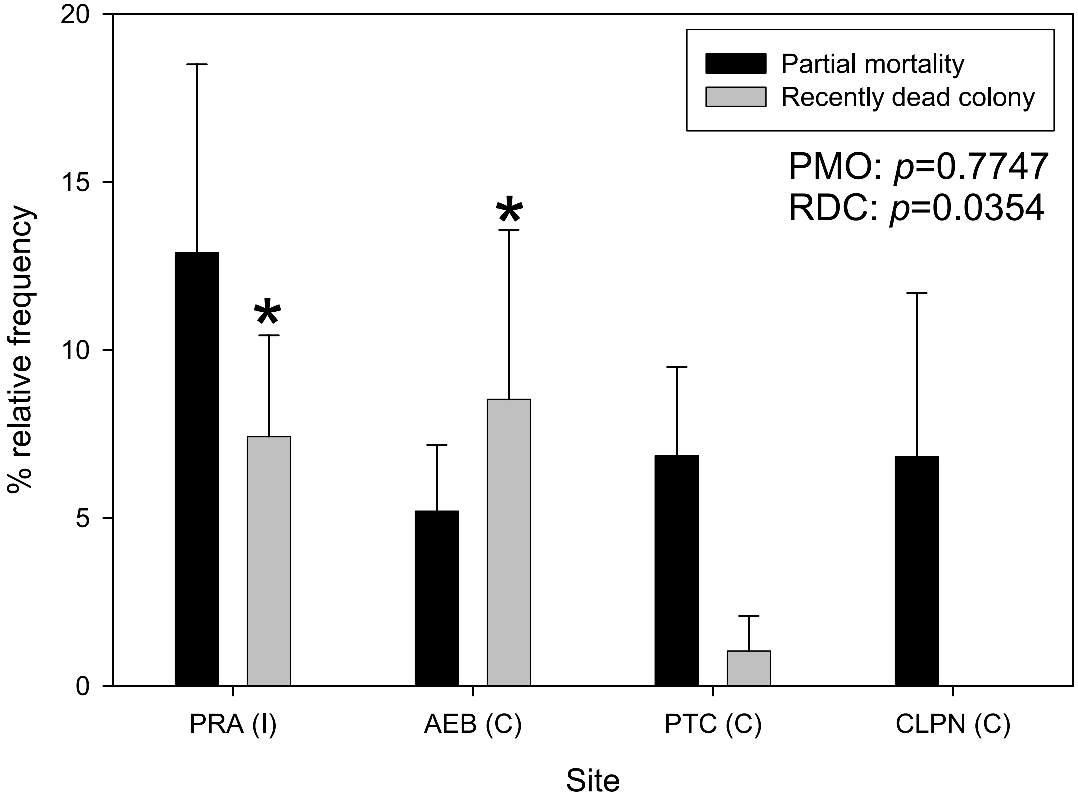


FIGURE 20. Percent relative frequency of hard coral partial colony mortality and recently dead colonies. I= impacted reef; C=control reef.

PRA (7.4%). There was no significant difference in total coral species diversity index (H'n) (Figure 21). However, hard coral H'n was significantly at AEB and PTC (*p*=0.0494). No significant differences were either detected in total or hard coral species evenness (J'n) (Figure 22). There was no significant difference in % zoanthid cover, but % sponge cover was significantly higher (*p*=0.0074) at AEB (Figure 23).

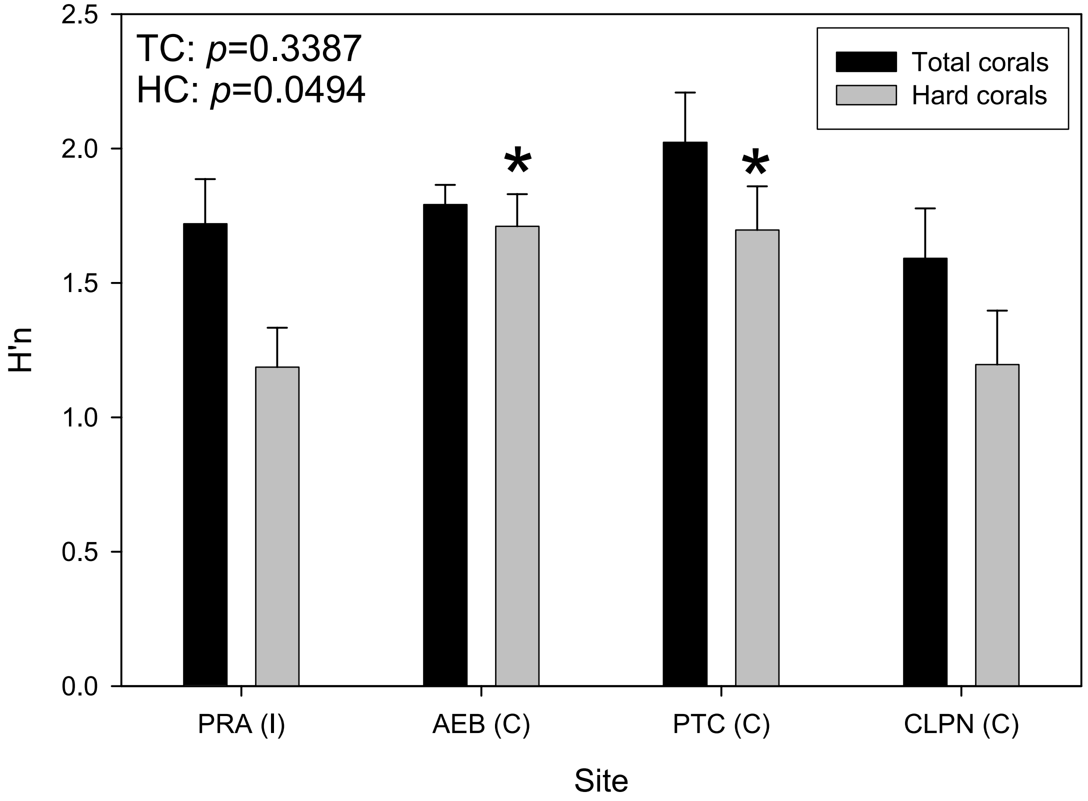


FIGURE 21. Species diversity index of total and hard corals. I= impacted reef; C=control reef.

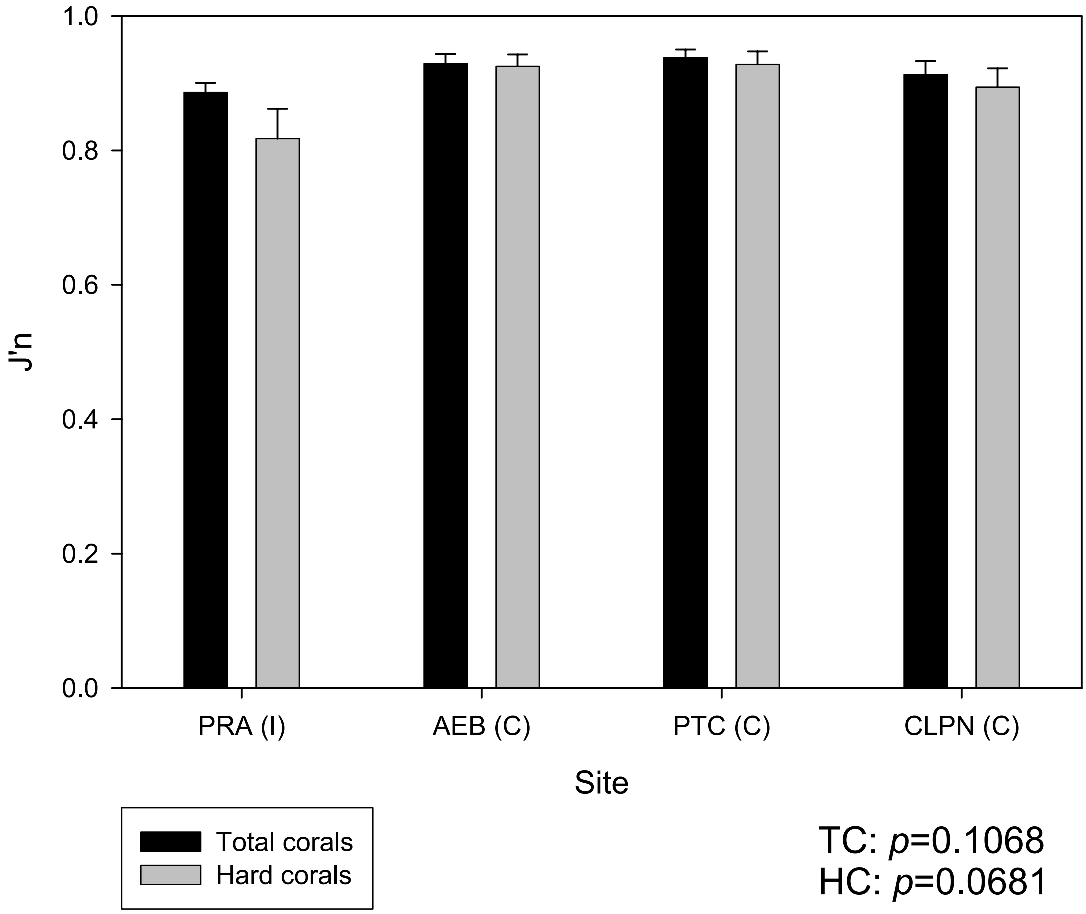


FIGURE 22. Species evenness of total and hard corals. I= impacted reef; C=control reef.

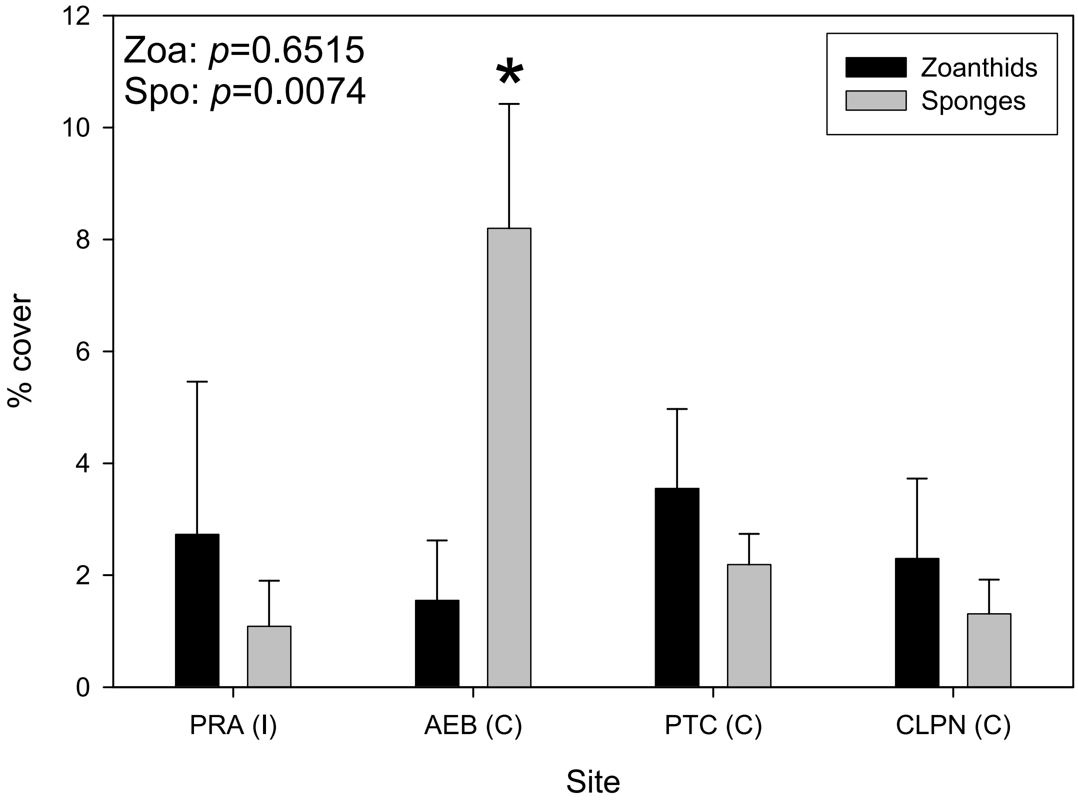


FIGURE 23. Percent zoanthid and sponge cover. I= impacted reef; C=control reef.

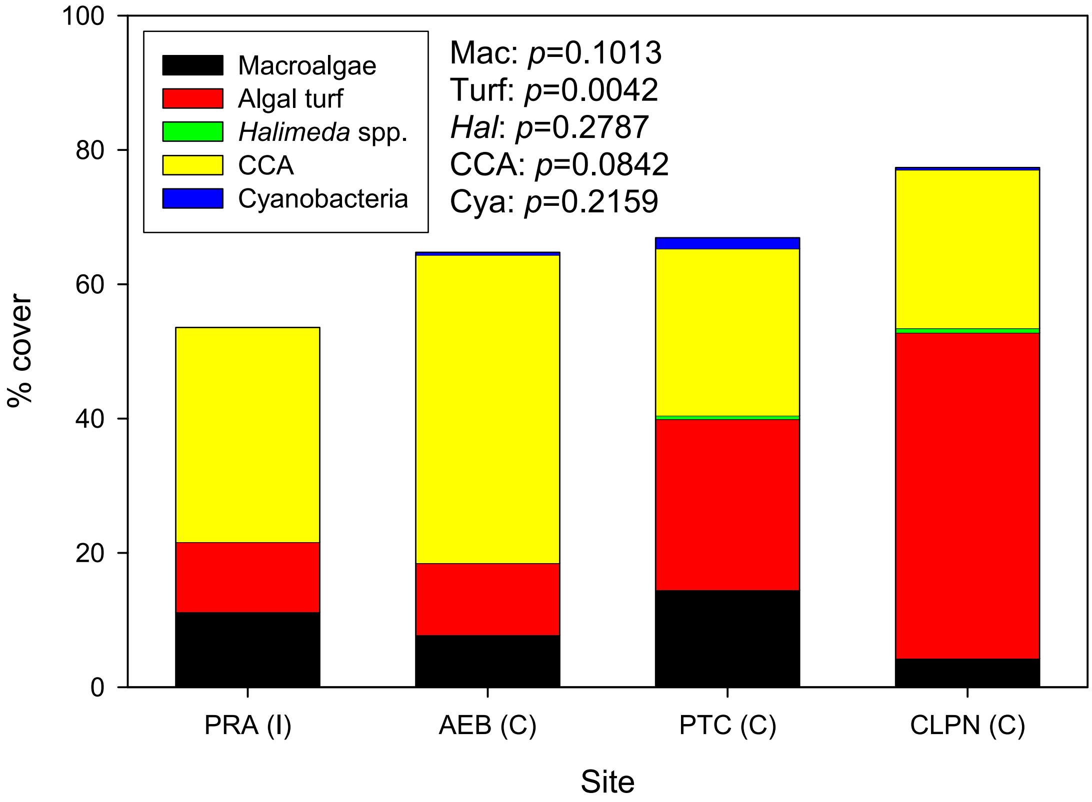


FIGURE 24. Percent algal and cyanobacterial cover. I= impacted reef; C=control reef.

Overall, algal cover was not significantly different among sites (Figure 24). At the functional group level, macroalgal, *Halimeda*, crustose coralline algal (CCA), and cyanobacterial % cover were not significantly different among sites. However, % algal turf cover was significantly higher at CLPN (p=0.0042). However, there was a tendency of higher % macroalgal cover at PTC and impacted site at PRA, with moderate values at ABE, and lower at CLPN. Percent cover of bare substrates, rubble and sand showed no significant differences among sites (Figure 25).

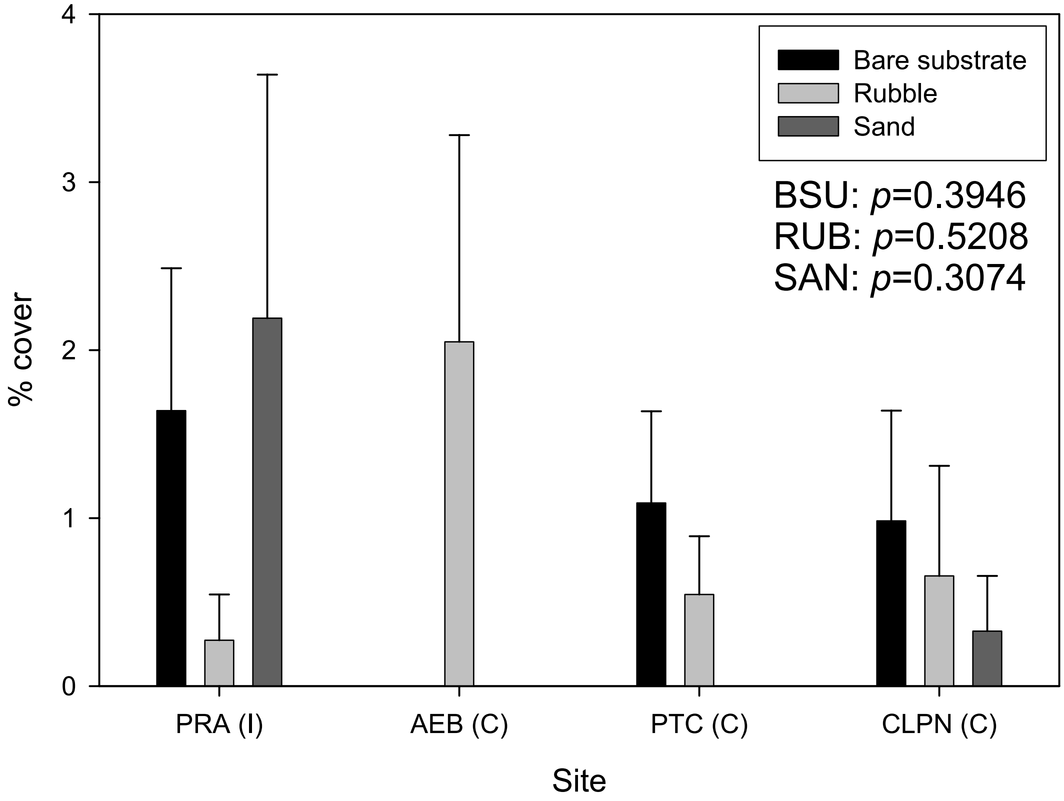


FIGURE 25. Percent cover of other benthic components (bare substrate, rubble, sand). I= impacted reef; C=control reef.

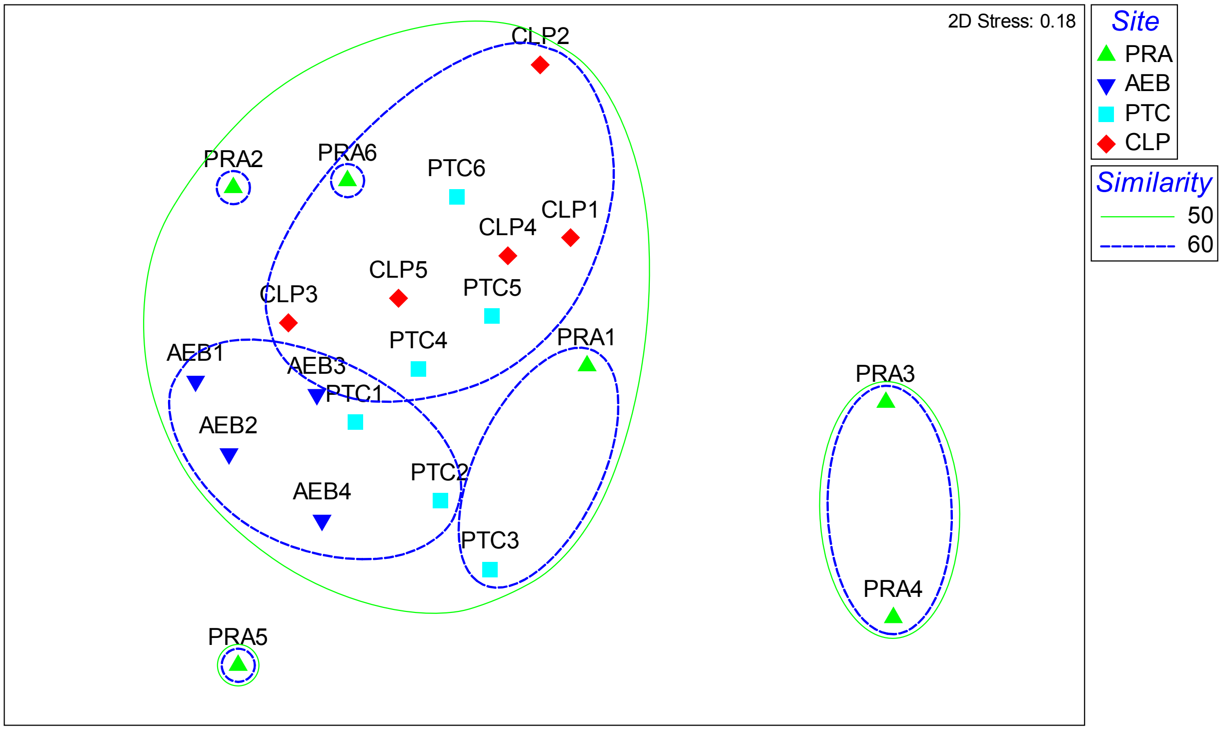


FIGURE 26. Multi-dimensional scaling analysis of the community structure of shallow-water coral reef benthic communities among sites. Data shows three basic clustering patterns at the 50% community similarity cutoff level with PRA5 transect forming an independent group, PRA3 and PRA4 forming a second independent group, and then a cloud of the rest of the sites. Seven different cluster patterns emerged at the 60% community similarity cutoff level, including individual clusters formed by PRA2, PRA5, PRA6, and PRA3-PRA4. Also, there was a cluster formed by PRA1 and PTC3, a moderate-sized cluster formed by AEB and PTC1-PTC2, and the remaining cluster formed by CLP and several PTC transects.

Multivariate tests of benthic community structure.

Three basic clustering patterns emerged at the 50% community similarity cutoff level with PRA5 transect forming an independent group, PRA3 and PRA4 forming a second independent group, and then a cloud of the rest of the sites. Seven different cluster patterns emerged at the 60% community similarity cutoff level, including individual clusters formed by PRA2, PRA5, PRA6, and PRA3-PRA4. Also, there was a cluster formed by PRA1 and PTC3, a moderate-sized cluster formed by AEB and PTC1-PTC2, and the remaining cluster formed by CLP and several PTC transects. The stress level of the MDS plot was 0.18, which is considered moderate to low. With a few exceptions, most of the communities showed a large degree of similarity and two-dimensional overlapping.

TABLE 2. Results of a one-way ANOSIM test of benthic community structure. Based on 5000 permutations. NS= Not significant (*p*>0.0500).

Factors	**Global R**	**Significance**
Global test		
Site	0.237	0.0004
Pairwise test – Site		
PRA (I) vs. AEB (C)	0.155	0.1290 NS
PRA (I) vs. PTC (C)	0.254	0.0130
PRA (I) vs. CLPN (C)	0.131	0.1560 NS
AEB (C) vs. PTC (C)	0.278	0.0430
AEB (C) vs. CLPN (C)	0.600	0.0160
PTC (C) vs. CLPN (C)	0.165	0.1190 NS

In spite of the fact that there was no significant differences in many of the individual benthic community parameters as tested using univariate statistics, a one-way multivariate ANOSIM test (Table 2) showed highly significant differences in overall benthic community structure among sites (*p*=0.0004). Benthic community structure at the impacted PRA site was significantly different from PTC (*p*=0.0130). Benthic communities at AEB were also significantly different from PTC (*p*=0.0430), and CLPN (*p*=0.0160). The benthic community at the impacted PRA was dominated by CCA (35.7%), followed by macroalgae (15%), scleractinian coral *Porites astreoides* (14.3%), filamentous algal turf (11%), and octocoral *Eunicea* spp. (5%). These account for 81% of the total % benthic cover. The benthic community at AEB is also dominated by CCA (31.3%), followed by filamentous algal turf (13.7%), sponges (11.4%), macroalgae (10.7%), and scleractinian coral *P.astreoides* (9.4%), accounting for 76.4% of the total % benthic cover. Dominance at PTC was less clear, but lead by CCA (19.4%), followed by filamentous algal turf (16.8%), macroalgae (16.7%), scleractinian coral *P. astreoides* (9.5%), and seafan *Gorgonia flabellum* (6.7%). These accounted for 69% of the total % benthic cover. Benthic communities at CLPN were dominated by filamentous algal turfs (35%), followed by CCA (22.4%), scleractinian coral *P.astreoides* (11.3%), macroalgae (9.6%), and fire coral *Millepora alcicornis* (5.3%). These accounted for 83.5% of the total benthic cover.

A SIMPER test revealed that benthic community differences between impacted PRA and AEB were mostly the result of higher % cover of sponges at AEB. Differences between PRA and PTC were mostly due to higher % filamentous algal turfs at PTC, while differences between PRA and CLPN were also the result of higher % filamentous algal turf cover at CLPN. Differences between AEB and PTC were similarly due to higher % filamentous algal turf cover at PTC. The same pattern repeated between AEB and CLPN, and between PTC and CLPN with higher % filamentous algal turf cover at CLPN.

Discussion

There was no evidence of direct impacts of landfill operations affecting the existing community structure of coral reefs adjacent to the landfill area in PRA. Existing differences among sites are largely the result of physical and oceanographical differences among sites. Actual conditions of coral reefs reflect basically similar patterns across sites, regardless of the distance from the landfill, suggesting that factors affecting corals are of larger geographical scales. These could be separated into regional factors and large-scale local factors. Regional factors included: sea surface warming, coral bleaching, hurricanes, and coral disease outbreaks. There was evidence of recent coral mortality during 2006 and 2007 at each site as a result of the 2005 unprecedented sea surface warming of the northeastern Caribbean that produced a mass coral bleaching event, and the subsequent mass coral mortality that occurred within the next year and a half. Most of the corals at each study site suffered massive bleaching (Hernández-Delgado, unpub. data) and many colonies of several taxa suffered significant mortality. There was also old evidence of coral disease outbreaks with the presence of dead standing colonies of elkhorn coral (*Acropora palmate*). Further, there was some old fragmentation of coral colonies as a result of past hurricanes.

Local factors include recurrent sediment-laden runoff pulses that may come from the landfill area, adjacent roads, and other adjacent landcleared sites. Also, there are recurrent raw sewage pulses coming from Ensenada Honda downtown area through the Luis Peña Channel with almost every ebbing tide. Thus nutrient pulses are affecting all study sites, but particularly, PTC, AEB and PRA. This may explain their slightly higher % macroalgal cover, and % cyanobacterial cover. The fact is that sediment-laden runoff pulses from the landfill site have been informed to occur (Hernández-Delgado, 2003, 2004), but their impact in coral reef community structure, given the lack of long-term monitoring at adjacent sites, and the significant temporal and spatial constraints of this study, did not allow us to measure it. This will require the use of proxy methods (i.e., detection of heavy metals accumulated in coral annual growth bands, detection of changes in coral annual growth rates, concentration of humic acids in annual growth bands) to determine if there have been spatio-temporal variations in landfill impacts.

Certainly, landfill operations do affect adjacent coral reefs in other ways. For instance, during strong high pressure-driven easterly winds, plastic bags often are blown by the wind and carried away to the water, ending up suffocating isolated coral colonies, or laying down on seagrass bottoms that constitute designated critical habitats for a resident endangered green turtle (*Chelonia mydas*) population. This will require stronger compliance with existing regulations to prevent plastic debris to be removed by wind.

Conclusions

Coral reef communities adjacent to the Culebra Island municipal landfill still support a high biodiversity. Although they show recent signs of decline, the spatial and temporal constraints of this study did not allow determine if such decline is related in any way to current landfill operations. However, frequent runoff pulses during heavy rainfall events and flying plastic debris still constitute a major environmental threat to adjacent coral reef and seagrass communities. Plastics are particularly a serious threat to local endangered turtle populations. Thus, determination of impacts will require further studies using coral proxy signals to address if there was any significant spatio-temporal pattern of landfill operation impacts on corals.

Acknowledgments

Part of the data collection was made possible thanks to the logistic support provided by Snapperfarm, Inc.

GEOTECHNICAL FIELD EVALUATION FOR DETERMINATION OF SUPERFICIAL LEACHATE MOVEMENT AT THE CULEBRA'S SANITARY LANDFILL AND ITS IMPACT ON THE LUIS PEÑA CANAL RESERVE

CULEBRA, PUERTO RICO

Victor Ortiz Nolasco, MEM, PE

Geo-environmental Consultant
VICTOR ORTIZ NOLASCO & ASOCIADOS

INTRODUCTION

This report presents the results of the geotechnical field evaluation conducted at the site of the existing facilities of the Culebra's municipality sanitary landfill. Culebra Island is one of a series of adjacent islands located to the east zone of Puerto Rico. These islands are part of the Puerto Rico municipalities where the most prominent are Vieques and Culebra. Culebra is located at least 27 kilometers to the east of Puerto Rico and 19 kilometers to the east of Virgin Islands. Its size is 12 kilometers length by 6 kilometers wide for an approximate area of 26.5 square kilometers. The location of the island of Culebra is shown in **Figure No.1**. Within this map the location of the existing municipal sanitary landfill was identified by a circle. It is found at Punta-Bahia Tamarindo located 3,000 meters northwest of the Culebra downtown area, bordering the Luis Peña Canal Reserve and 500 meters southwest of Laguna del Flamenco.

This investigation is part of a scientific study actually undertaken by Dr. José Norat, representing the Department of Environmental Health, Graduate School of Public Health, Medical Sciences Campus of the University of Puerto Rico in Río Piedras (UPR). Dr. Norat is working in a project of investigation with Drs. Hernando Mattei and José Seguinot from the Medical Sciences Campus, and Drs. Edwin Hernández and Maritza Barreto from the Rio Piedras Campus, both of the UPR. Their study was entitled; "Historical Development of the Municipality Landfill in the Eastern Border of the Luis Peña Canal Reserve in the Municipality of Culebra, Puerto Rico and its Potential Impact on the Reserve", and is sponsored by the Puerto Rico Department of Natural and Environmental Resources (known as DRNA by its Spanish acronyms) and the National Oceanic and Atmospheric Administration (NOAA). Their concern is related to the possibility of leachate contamination migrating from the higher zones of the sanitary landfill to the lower areas, and if occurring characterize the contaminant concentrations by monitoring well sampling and testing in order to compare those results with the ones to be further collected and sampled along the coral reef within the Luis Peña Canal Reserve.

The objective of this investigation is to observe the topography, area and superficial soil conditions of the site where the municipal sanitary landfill was located in order to identify those areas with a possibility of creating a leachate impact to the nearby Luis Peña Canal Reserve and to the Punta Tamarindo coast. Also this evaluation includes the field identification of a series of groundwater and methane gas monitoring well; determine their locations and structural conditions within the sanitary landfill site; and to present our findings related to the presence of leachate and its impact by leakage, infiltration or runoff to the Luis Peña Canal Reserve and its related coral reef life.

Parallel to this investigation Altol Chemical Environmental Inc. (ALTOL) performed a series of field sampling and testing to water samples collected on three (3) monitoring wells and also performed structural integrity tests on four (4) existing wells. Full RCRA laboratory tests are to be performed on these water samples and their results are to be submitted by Altol in a separate report. An available location plan of the existing sanitary landfill including the location of water and gas monitoring wells is shown in **Figure No. 2**.

SCOPE OF WORK

The scope of work performed for this project is presented in the following subsections.

a) Site Reconnaissance - existing conditions of the site were visually inspected.
b) A preliminary site plan was used as the main source of site data. Also, a series of photographs were taken for obtaining a visual data of the site. Available environmental documents were reviewed.
c) Additionally, interviews with engineers, administrators and sanitary landfill operators were performed for data acquisition and historical information.

FIELD EXPLORATION

Our first visit to the Island of Culebra was held on December 13, 2006, at 10:30 a.m. The staff was composed by Dr. José Norat, who is in charge of this investigation for the UPR; Carlos Esteves, Rubén Hernández, which are students of the Environmental Health Department of the Graduate School of Public Health of the UPR; and the undersigned. Please refer to **Photographs No. 1 and 2** which shows the visiting staff and personnel of the municipality of Culebra. As soon as we arrived to the island a meeting was arranged with Mr. Enrique Carrión, the Director of Public Works, and engineer Arnaldo Just, an engineering consultant, both representing the municipality of Culebra. The scope of our investigation was explained to them in order to have their local support, give us mobilization to the sanitary landfill and to obtain related data and any technical information necessary for the investigation.

Mr. Carrión and one of his employees mobilized us to the site of the sanitary landfill in two official municipality vehicles. During the trip to the site Mr. Just and Mr. Carrión informed us that the sanitary landfill is under operation since the year of 1971 and actually this facility is receiving municipal and/or domestic wastes from a population of approximately 3,500 persons generating an average waste amount of 6 tons/day. The waste is collected in a daily basis by two rear-loaded compactor trucks which transport it to the sanitary landfill. Most of the domestic waste is collected on Monday because of the high increment in visitors and tourist getting in the island on weekends.

Once in the facilities of the municipal sanitary landfill we met with the only employee present at site who also was in charge of operating the 1972 D-6 Caterpillar Bulldozer; in charge of spreading the solid wastes, its compaction and placing of the fill cover material. His name is "Don Nato", as he's been working on the landfill for the past 35 years. He was working in the sanitary landfill when the cited heavy equipment was acquired from the past municipal administration in 1972.

Don Nato showed us the location of all of the existing groundwater and gas monitoring wells constructed at site whose design, data, and related information was not available neither at the landfill's Administration office nor in the municipality Public Works Administrative offices. A total of six (6) monitoring well locations were observed as show in **Photographs No. 3, 4, 5, 6 and 7.** These consist of 6-inches watertight manhole cover with padlock, having an average height of 5 feet above ground which are identified by green color numbers within a yellow paint media along the steel protective casing. A water monitoring well (MW-1) located at the east side zone of the landfill was destroyed and permanently damaged by impacts of car chunks and heavy metal pieces during the past Hurricane David, as Don Nato mentioned, and is shown in **Photographs No. 8, 9 and 10.** This monitoring well is as far as 25 meters from the Luis Peña Canal shore which was also included in our visual reconnaissance and no evidence of leachate or any other superficial contaminant, debris or garbage was observed along this zone, as shown in **Photographs No. 11 and 12**. The rest of the monitoring wells are located around the south area of the landfill and are not impacted by the landfill operations. As part of the field work performed at the landfill during this visit, the students of Dr. Norat works with an electronic equipment (a Geographic Information System (GIS)) for assigning geographical coordinates to them each one of the monitoring wells as shown in **Photograph No. 5**. After all of the wells were located we performed a visual reconnaissance along the landfill-deposit area and the findings are discussed in the forthcoming sections.

As information provided by Mr. Just and Mr. Carrión, they understand that these observation wells were constructed by a geotechnical engineering firm named GeoPractica in 1991, but at this time they don't have any available information regarding to the design, construction, development and monitoring of these wells. To our surprise Don Nato mentioned that as his best knowledge he doesn't see any person or technicians visiting the site for taking water or gas measurements on these wells since their construction in 1991. Mr. Carrión told us that personnel of the Puerto Rico Environmental and Quality Board (EQB) visited the site on July 2006, approximately, to observed the sanitary landfill conditions, the monitoring well locations and other applicable environmental features in order to present to the municipality of Culebra their findings and deficiencies for further compliance. He also mentioned that after this visit of EQB to the landfill the Municipal Administration submits their "Sanitary Landfill Compliance Plan" (the Plan) to the Puerto Rico Solid Waste Authority (PRSWA). This Plan was prepared under the supervision of engineer Gil Nieves, who is the consultant for the municipal administration of Mr. Abraham Peña, the actual city Major, on environmental and public work projects for the past 25 years. At the time of this report this Plan hasn't been approved, as they mentioned to this consultant.

At the evening we met with Mrs. Militza Pérez, the Municipal Administrator, and the above mentioned personnel at the City Hall. At this particular time they don't have any technical information regarding to the landfill operation, well monitoring or engineering plans of the site. They tell us that the person who better knows what information is available and where is located is engineer Gil Nieves who is working for the municipal administration since 1970. A meeting was arranged with Mr. Nieves in his Puerto Rico office for establishing a second visit to the site in order to obtained from him available data corresponding to the sanitary landfill compliances and/or regulations requested by federal and local agencies.

FIELD EVALUATION

I. Geology of the landfill area

According to the PREQB map *Geologic Map of the Culebra Quadrangle*[1], the site is underlain by volcanic rocks corresponding to the TKs Formation. It consists of sandstone, siltstone, conglomerate, lava, tuff, and tuffaceous breccia all of late Cretaceous Age. This formation covers about 90% of the Island of Culebra and is located predominantly around the west, south and east areas. The north zone of the island is covered by alluvium, diorite and volcanic toba.

II. Available Subsoil Exploration Data

Information provided by Dr. Norat includes copies of two geotechnical engineering reports prepared by Geopractica, Inc., in 1991 and 1992, which are part of the available Environmental Impact Document (DIA, by its Spanish acronyms) of the landfill. The subsoil profile encountered during the investigation performed by Geopractica, Inc. in March 14, 1991[2] indicates that their findings are in agreement with the geologic setting described in the geologic literature. Occasional small landslide deposits were observed in several areas of the project, specifically at the foot of the slopes which were brought there by gravity. The geological setting existing at the project site may be broadly characterized into three main soil formations; (1) upper residual soil horizon consisting of alternating layers of hard clays and silty sands extending to about 3 feet of depth, (2) saprolitic silts and the weathered and partly weathered rock sampled as angular rock fragments with fine gravel-size rock fragments and silt with fine sand which is extended to about 5 feet of depth; and (3) the un-weathered fresh volcanic rock basement which extends to about 15 to 20 feet of depth. Based on our visual observations on exposed cuts around the site this rock consists of an extremely hard rock, fresh, thin-bedded, dark gray to greenish black in color, tufacceous conglomerate with fine cristalline diabase and dolomitic limestone and quartz. Some isolated boulders were observed around the exposed cuts along the site and others were deposited in some areas of the lot as part of the earthwork operation for fill extraction. Although the description of the various earth materials encountered is detailed in the boring logs within the subsoil exploration reports, these were classified in general groups, previously mentioned, in order to simplify the discussion. The residual soils are those consisting of silts, clays and the combination of both and are derived from the parent rock. Saprolite is completely weathered rock sampled as indurated silt, elastic silt and silt, and is the transition between the parent rock and the residual soils. Highly weathered rock was penetrated with the hollow stem augers and samples as rock fragments mixed with fine-grained materials. Penetration resistance was extremely high. Lastly, sound rock required the use of diamond core drilling in order to be penetrated and sampled. Its weathering degree varies from highly to moderately weathered. This report also mentioned the installation of four monitoring wells to depth of 20 to 25 feet consisting of 4-inch diameter PVC casing with screen sections surrounded by coarse sands which were sealed with expandable bentonite plugs and finished to grade in watertight manhole covers sealed with cement slurry. A copy of their typical construction is included in **Appendix A**. The report do not stated which of these wells are for water sampling or for methane gas monitoring. It refers to the boring logs where the water level was registered in two wells identified as Borewell No.1 (water near ground surface); and Borewell No.2 (water level at 10'-03"); while Borewell No.3 and No.4 do not revealed the presence of water within their depths. The location of these borings and wells is also included in **Appendix A.** The conclusions of this study calls for the use of stable slopes with a 1(H):3(V) inclination; the use of heavy excavation equipment for establishing the cut operation around the natural soils of the area to depth in the order of 5 to 15 feet where the very dense fresh rock will be found.

The second geotechnical evaluation was performed by Geopractica, Inc. in February 19, 1992[3], under a contract with the municipality of Culebra. This investigation deals with information to determined the amount of sanitary landfill available, quality of the fill including depth to the fresh rock, excavations and determination of the permeability of the rock. The results of the study (covered by four shallow borings to depths of 6 to 10 feet below existing grade found at the time of the field work) indicates the same superficial soil conditions found in the first study but without reaching the groundwater level. The location of these new borings is included in **Appendix B**. The results of the study indicates permeability values for the very dense fresh rock found at site varying from 0.001 and 0.5 US gpd/ft^2; while for the superficial weathered and fractured rock it was measured as 194 gpd/ ft^2. These values indicate that the fresh rock of the area will be considered as an impermeable surface which will cause that the leachate and water runoff will flow between this surface and the domestic fill looking to the lower areas around the sanitary landfill. The study mentioned that excavation for fill will be limited to depths varying from 6 to 10 feet below existing grade without the use of explosives.

III. Visual Observations and Inspection

During our visual inspection to the sanitary landfill on December 2006 we have noted that all of the existing wells are identified by a bluish green number painted over a yellow color surface along the protective casing with numbers varying from 2 to 6. Once the location of the wells was completed we walk around the southern area of the landfill in a northwest direction in order to observe the lower and higher zones of the site where leachate and soil surface erosion will occur having a potential runoff that will reach the Luis Peña Canal Reserve. Closed to the top of the existing dirt road located to the south border of the landfill deposit area we observed two areas where leachate is present. In both of these points the leachate flow is running to the southeast, and is heading to the south zone located far away from the Luis Peña Canal Reserve. Please refer to **Photographs No. 13, 14 and 15**. Another leachate leak is observed at the west area of the landfill which ends in a small stagnant water pond mixed with debris. This point is located in a higher area of the landfill and is closed to the Luis Peña Canal Reserve as shown in **Photographs No. 16 and 17.** Based on information obtained from Mr. Nato, (which is the landfill operator and the only employee present at the time of our visit), he told us that heavy rains falls down in the zone during the last two days and that some little stagnant waters ponds are dispersed around many places of the landfill, referring to the stagnant water ponds observed in **Photographs No. 18, 19, 20 and 21**. An additional leakage leak area was observed closed to the existing abandoned structures located at the south area of the landfill, as shown in **Photographs No. 22 and 23**. Actually, the landfill operator is placing the domestic waste around the north and northwest areas of the site as shown in **Photographs No. 24 to 27**. **Photograph No. 28** shows one of the rear-loaded garbage trucks used by the Municipal Administration of Culebra.

IV. Landfill Methodology for Domestic Waste Placement

Information provided by Mr. Nato indicates that he was in charge of working with the preparation of the excavation areas and the domestic waste treatment within the landfill site. These areas consists of a series of trenches having dimensions of 5 feet deep by 5 feet wide with a length of 12 to 15 feet in which the domestic solid waste was deposited and compacted in 3 feet thick layers using a bulldozer Caterpillar D-8 or similar, and then backfill with an 8-inches thick layer of the excavated material, and continue this process until reaching the actual surface elevation. No geotextile or any other polyester fiber is used at the bottom of the trench as mentioned by Mr. Nato. **Figure No. 3** shows the area and the estimated length of trenching excavation performed by Mr. Nato since the opening of the landfill site.

Along the exposed cuts located around the landfill northeast area the excavated material mostly consist of a superficial clayey silt, clay and sandy silt followed by a very dense highly weathered rock having some fine to medium sand and silt, traces of clay and a yellowish brown to dark brown color with some oxidized stains. Isolated volcanic rock boulders with different sizes and weathering degrees are located in many areas within the exposed cuts. This material is very difficult to excavate with conventional excavation equipment, a reason why Mr. Nato excavates not more than 5 feet below the soils surface for constructing the trenches. Based on this information we have prepared Profile No. 1, which is shown in **Figure No. 4**, using information inferred from the site's topography and cuts including the volcanic origin of the soils for illustrative purposes. Using this cross section as reference we have the opinion that most of the leachate generated by the sanitary landfill (with the exception of the surface runoff) is to be trapped within its own trench walls and the process of infiltration will depend on the permeability of the natural soils, which in the case of the fresh bedrock it ranges from 0.001 and 0.5 US gpd/ft^2 while for the superficial saprolitic and weathered clayey/sandy/gravelly soils it was measured as 194 gpd/ ft^2, as mentioned in the geotechnical report. Actually these trenches are totally covered by layers of domestic waste and backfill with thicknesses in the order of 5 to

10 feet extending from the lower boundary of the landfill to the south, to a distance of about 100 feet to the north. From this point off Mr. Nato construct a horizontal cut where the domestic waste and backfill were deposited to the actual elevations, as illustrated in Figure No. 4.

Based on the above we have the opinion that most of the exposed leachate is coming from the higher areas of the landfill which are possibly collected along the existing narrow trenches filled with domestic waste and backfill that maybe arises from an overflow occurring during heavy rains in each trench. Also, superficial leachate runoff will occur from leakages at different zones of the landfill especially during rainy seasons. This sanitary landfill do not have any control for runoff waters coming from the higher areas of the site during heavy rain events which can easily transports traces of leachate that shall reach the vicinities of the Luis Peña Canal and the Bahia de Tamarindo coast. The amount of superficial leachate generated by the sanitary landfill can be considered as low as observed along its vicinities.

An abandoned remnant of an apparent former Vehicle Maintenance Area was observed located to the northeast area of the sanitary landfill where a spill of black motor oil is covering its concrete floor. This structure has an U-shape geometry and consists of a reinforced concrete structure having a height of about 10 feet and wall’s thickness of 12 inches. It needs to be demolished and/or cleaned as soon as possible to eliminate the potential risk that represents to the Luis Peña Canal Reserve and its coast if these contaminants migrate by gravity during a heavy rain event throughout the sloppy zone facing the structure.

V. *Field Water Sampling and Integrity Tests on Monitoring Wells*

On August 16, 2007 we visited the site for the performance of the field sampling and determination of the condition of the wells and evaluating the structural integrity of the PVC casing used in their construction. As information provided by personnel of the municipality of Culebra these wells don’t be monitor since its construction in 1991. A CAD drawing showing the landfill location plan was provided by Dr. Norat, and is included as **Figure No. 5.** It was used as reference for locating the existing monitoring wells with the information gathered from the field using the GIS system of coordinates. All the well locations are presented in this figure.

The chemical laboratory contracted by the UPR in charge of the field sampling is Altol Chemical Environmental, Inc, under the direction and supervision of Mr. Carlos Negrón. The staff was composed with Mr. Orville García and Wilfredo García, representing Altol; Mr. Ammon DeLong, who is the technician in charge of the performance of the integrity test on the wells using a closed circuit camera and recording equipment in a VHS format who was contracted by Altol; Mrs. Julissa Nieves, representing the Graduate School of Public Health of the UPR in charge of assigning coordinates to each well location; and the undersigned, representing Geocom Engineers Inc, who was in charge of the coordination of the field work, including obtaining the municipal support of transportation and permits, and the supervision of all of the work performed at the site, including geotechnical observations and leachate data information.

The field work started at 9:30 a.m., and was performed under a bright sunny day with high relative moisture. The vegetation was very high and the access was difficult for reaching the well locations. The operator of the heavy equipment working at the sanitary landfill (which is Mr. Nato using a trackcavator Caterpillar D-8) help us in the cleaning operation by performing a very shallow superficial dirt road creating an easy access to all of the five observation well locations. Once this operation was completed, we have identified the wells to be tested by its actual numbers, and using the reference design data obtained from the previous geotechnical engineering report dated March 14, 1991. This report described in its Figure No. 2-"Typical Well Construction" the design of all of the wells using a 4-inch diameter PVC raiser and screen which are the ones constructed for water sampling. A note was included within this figure indicating that "all well materials are 4-inches diameter schedule 40 flush joint PVC pipe", but they are not identified as methane gas or water monitoring wells.

From the six (6) well locations identified only three of them were constructed using a 4" diameter PVC pipe and those were identified as MW-2, MW-3 and MW-4A. Their depths do not exceed 20 feet and are completely dry when we inserted the electrical water level tape for measuring the depth to the probable groundwater level. We assume that these wells are for the monitoring of methane gas because all of them have a PVC cap for preventing the gases to escape. The other two monitoring wells, identified as MW-4 and MW-5, are constructed using a 2-inch diameter PVC raiser and screen and their depths are measured as 35 and 30 feet, respectively, with groundwater level measured at 24.3 and 19.69 feet below existing ground elevation, respectively. These measurements are taken between 11:30 a.m. to 12:30 p.m. in these two wells. Monitoring well identified as MW-1 in available plans is the one that collapsed and was clogged during the flood events of Hurricane David. Only a broken section of its protective steel pipe is located within the vicinities of this well. No evidence of the well's PVC casing or borehole was observed around this location. After finishing the identification and description of the monitoring wells ALTOL started the sampling following its protocol and procedures. Table No. 1 shows the description of the wells located at site and tested for structural integrity or groundwater testing.

TABLE NO. 1

Well Number, Depth and Field Data

Well Number	Depth, ft*	Groundwater Level, ft	Average pH and Temperature (°C)	Structural Integrity of the Well**
MW-2	13.49	N.F.	--	Not Tested
MW-3	20.42	N.F.	--	Excellent
MW-4	34.7	24.3	7.03 (31.1)	Excellent
MW-5	29.9	19.69	7.38 (33.2)	Excellent
MW-4A	21.06	N.F.	--	Excellent

* Measure from the top of the protective casing on each well location, which is typically 5 feet above existing ground elevation.

**A VHS video tape was included as part of this report, showing the actual conditions of the PVC pipes and screen of the wells tested.

The water sampling protocol, procedures and testing followed by ALTOL are presented in **Appendix C** in a Spanish version[4]. Full RCRA testing is to be performed on the water samples collected. Tests such as ignitability, corrosivity, reactivity, metals (TCLP), volatiles (TCLP), semi-volatiles (TCLP), pesticides (TCLP) and herbicides (TCLP) are included in RCRA tests. The Chain of Custody Form #14994 was presented to the undersigned as soon as the samples were transported to Altol Lab and a copy is included in **Appendix C**. The results of the chemical testing are to be presented in a separate report to the office of Dr. Norat and the UPR. A copy of the video in VHS format is included with this report. All of the wells tested show no evidence of deterioration, breakage, cracks, seals and/or any other structural damage along its respective lengths.

CONCLUSIONS AND RECOMMENDATIONS

Leachate should be defined as a liquid that has percolated through solid waste and has extracted dissolved or suspended materials from it. In most landfills the liquid portion of the leachate is composed of the liquid produced from the decomposition of the wastes and liquid that has entered the landfill from external sources, such as surface drainage, rainfall, groundwater, and water from underground springs. Under normal conditions, leachate is found in the bottom of the landfills. From there, the movement is through the underlying strata, although some lateral movement may also occur, depending on the characteristics of the surrounding material.

The rate of seepage of leachate from the bottom of a landfill can be estimated by Darcy's Law by assuming that the material below the landfill to the top of the water table is saturated and that a small layer of leachate exists at the bottom of the fill. Under these conditions the leachate discharge rate per unit area is equal to the value of the coefficient of permeability K expressed in meters per day (feet per seconds). The computed value represents the maximum amount of seepage that would be expected, and this value should be used for design purposes[5].

In this particular landfill four (4) field permeability tests were performed on the natural soils by Geopractica, Inc. in February 19, 1992. Two of these tests were performed at a depth of 9 to 10 feet below existing grade within a brown and olive volcanic rock media having a coefficient of permeability in the range of 2.273×10^{-9} ft/sec. to 6.664×10^{-7} ft/sec.(which is equivalent to 0.001 US gpd/ ft^2 to 0.43 US gpd/ ft^2, respectively). The other two tests were performed on superficial residual and weathered rock at a depth of 5 to 6 feet and the results show a coefficient of permeability in the range of 6.143×10^{-7} ft/sec. to 3.007×10^{-4} ft/sec.(this is equivalent to 0.397 US gpd/ft^2 and 194.252 US gpd/ft^2, respectively). These values indicate that the volcanic bedrock encountered below the sanitary landfill area is relatively impermeable and that the low leachate movement will be flowing between this surface and the sanitary landfill looking for the lower points of the site.

Composition of Municipal Landfill Leachate

The composition of municipal landfill leachate exhibits noticeable temporal and site-specific variation. This variation in chemical and microbiological characteristics is attributed to a combination of factors including landfill age, waste nature, moisture availability, temperature, pH, depth fills, and compaction (USEPA, 1995; Viraraghavan and Singh, 1997). As a result, reported concentrations of leachate contaminants range extensively, probably spanning several orders of magnitude. The internal biological and chemical transformations within landfills occurring as wastes decompose have a strong relationship with leachate characteristics. In general, these biochemical processes are divided in time into aerobic, anaerobic acid, initial methanogenic, and stable methanogenic phases. Over a longer time frame, three additional phases including methane oxidation, air intrusion, and carbon dioxide phases are speculated to follow (Kjeldsen et al., 2002). The comparison of qualities of landfill leachate and municipal wastewater is shown in Table No. 2. The amount of leachate produce is directly linked to the amount of precipitation around the landfill. Also, the amount of liquid waste in the landfill affects the quantity of leachate produced.

Organic constituents, ammonia, and heavy metals in leachate are the three primary treatment and disposal issues, in addition to high total dissolved solids concentrations. Organic constituents are typically characterized in terms of chemical oxygen demand (COD), 5-day biological oxygen demand (BOD5), and total organic carbon (TOC). Generally, high COD (3,000-60,000 mg/L) and high BOD5/COD ratio (> 0.6) characterize leachate from young landfills (< 1-2 years old), and, in contrast, relatively low COD (100-500 mg/L) and low BOD5/COD ratio.(< 0.3) characterize mature leachate from old landfills (> 10 years old) (Tchobanoglous and Kreith, 2002).

TABLE NO. 2

Comparison of water quality of untreated municipal wastewater and landfill leachate

Untreated Municipal Wastewater				**Landfill Leachate**	
(Liu and Liptak, 2000; Tchobanoglous et al., 2002)				**(Lu et al., 1985; Andreottola and Cannas, 1992; Qasim and Chiang, 1994; Tchobanoglous and Kreith, 2002; ; Qian et al., 2002)**	
Indicators	Weak	Medium	Strong	Young	Old
pH				4.5 –7.5	6.6 – 7.5
COD (mg/L)	250	500	1,000	3,000- 60,000	100 - 500
BOD$_5$ /COD	N/A	N/A	N/A	0.6 - 1.0	0 - 0.3
TOC (mg/L)	80	160	290	1,500 - 20,000	80 - 160
TSS (mg/L)	100	220	350	200 – 2,000	100 - 400
TDS (mg/L)	250	500	850	3,90-44,900	
Hardness (mg/L as CaCO3)				300 – 10,000	200 - 500
Alkalinity (mg/L as CaCO3)	50	100	200	470-57,850	
Ammonia nitrogen (mg/L)	12	25	50	10 - 800	20-40
Total P (mg/L)	4	8	15	5 - 100	5-10
Chloride (mg/L)	30	50	100	200 -3,000	100 - 400

Sulfate (mg/L)	20	30	50	8-1,400
Arsenic (mg/L)				0.0002-1.6
Barium (mg/L)				0.08-5
Cadmium (mg/L)				0.0007-0.15
Lead (mg/L)				0.005-1.6
Mercury (mg/L)				0.0002-0.05
Nickel (mg/L)				0.02-2.227
Copper (mg/L)				0.004 – 9

N/A: Not Available

High molecular weight organics account for a higher fraction in mature leachate, whereas a larger amount of low molecular weight organics is found in young leachate. Among these organics, high molecular weight fractions possess complex structures with functional groups containing nitrogen, oxygen and sulfur. In contrast, low molecular weight fractions have linear chains substituted by oxygenated functional groups (Calace et al., 2001). Phthalate esters, volatile aromatics, aromatic sulphonates, chlorinated volatile hydrocarbons, phenols, cresols and numerous other organic pollutants have been identified in various concentrations in landfill leachate (Jimenez et al., 2002). Ammonia nitrogen in leachate may be present in concentrations up to 2,000 mg/L. Ammonia, released from wastes mainly by decomposition of protein, may kill microorganisms in biological processes. And, ammonia concentrations may persist in the leachate with time, so that ammonia has been regarded as the most problematic constituent in leachate over the long term (Kjeldsen et al., 2002). Heavy metals can be a significant concern in leachate, although Kjeldsen et al. (2002) reported that metals in leachate were found at concentrations at or below U.S. drinking waster standards due to adsorption, precipitation and complexation in the landfill.

Microbiological characteristics in leachate are less well known than their chemical counterparts. A significant bacterial population associated with municipal landfill leachate of fresh refuse was observed in several studies (Ware, 1980; Donnelly and Scarpino, 1981; Sleat et al., 1989). Viruses are only occasionally detected in the leachate (Lu et al., 1985). Little information is available on the presence of fungi and parasites in the leachate. Certain landfill conditions, such as high temperature, low pH and old landfill age, and chemical characteristics of the leachate including heavy metal concentrations contribute to inactivation of bacteria and viruses (Lu et al., 1985; Andreottola, 1992)[6].

In March 1992 an Environmental Impact Study (DIA Final, by its Spanish acronyms) was submitted by the Municipal Administration of Culebra to the Puerto Rico Environmental Quality Board (EQB) and the Fish and Wildlife Service (FWS) and others for obtaining their comments to the content of the document. The document was entitled: “Declaración de Impacto Ambiental, Ampliación del Vertedero Municipal de Relleno Sanitario de Culebra, Puerto Rico”[1]. Both agencies presented some recommendations requesting additional studies and changes in the proposed design of the sanitary landfill extension. The most prominent recommendation deals with the protection of the coast of Punta Tamarindo and Luis Peña Canal located to the south and east areas of the landfill against leachate. On the basis of our field investigation only three (3) zones of potential leachate leakage were identified as show in **Figure No. 6**. These zones are identified in this figure as zones Z-1, Z-2 and Z-3. Zone Z-1 is located at the northeast area of the landfill were a superficial leachate leakage was identified as evidence by Photographs No. 13 to 15. Zones Z-2 and Z-3 are located to the south zone of the landfill and consists of concentrated leachate leakages facing an existing dirt road having a slope inclination of about 35 degrees going down to the east of the landfill where in some instances will migrate to the lower areas of the landfill heading to an existing pond closed to the Bahia Punta Tamarindo and its coast, as show in Photographs No. 16 to 21. It is possible that in an event of heavy rains this substance will migrates to these zones creating an environmental impact to the area if some protection measures are ignore. It is understandable that the municipal administration of Culebra is looking for funds in order to invest in the landfill improvements including its new expansion. But that process will takes a long time and certainly some rain events will occurs creating a potential menace to the Luis Peña Canal Reserve and the Punta Tamarindo coast. In order to implement remediative measures until the funds and the landfill expansion occurs, we recommends the construction of a clay dike along the perimeter of the Zones previously mentioned such to control the runoff water migration and prevent the possibility of leachate contamination to the Luis Peña Canal Reserve and Punta Tamarindo coast. **Figure No. 7** shows the proposed location of this earth dike and its recommended geometry.

If the sanitary landfill expansion is approved by the regulatory agencies it is recommended the implementation of all of the runoff water control and leakage management presented in the "DIA Final" document as soon as possible specially the recommendations regarding to the leachate control closed to the Luis Peña Canal and its coast.

LIMITATIONS OF THIS REPORT

This report is based on all concepts, reports, parameters and constraints which have been made known to us. The conclusions and recommendations presented in this report are the result of our best evaluation of the data revealed in the above mentioned documents, and of the engineering properties of soils and rock as obtained in laboratory tests performed in accordance with geotechnical engineering standards. Interpretations and judgments based on these data may differ from actual conditions since variations in the nature and behavior of subsurface materials may occur within short distances.

Photograph No. 1 & No.2- Visiting staff nearby Culebras's City Hall and at the landfill area

Photograph No. 3 & No.4- Location of Monitoring Well MW-2 (methane gas observation well). Looking to the East

Photograph No. 5 & No.6- Location of Monitoring Wells MW-3 & MW-4 (methane gas and water observation wells, respectively). Looking to the East

Photograph No. 7- Location of Monitoring Well MW-5 (water monitoring well). Looking to the southeast

Photograph No. 8- Location of Monitoring Well MW-1 (water monitoring well). Destroyed by Hurricane David. Looking to the West

Photographs No. 9 & 10- Monitoring Well MW-1. Looking to the South and North, respectively. It was closed to the Luis Peña Canal Reserve, as far as 25 meters

Photographs No. 11 & 12- Showing the exit area of the runoff waters coming from the nearby Monitoring Well MW-1 location to the Luis Peña Canal shore. Looking to the East and North, respectively. No evidence of leachate and any other superficial contaminant are observed along these zones. The very-fine white sand and medium to coarse gravel looks clean.

Photographs No. 13 & 14- Looking to the west showing two leachate-prone surface areas running to the southeast. This area is identified as leachate Zone Z-1

Photographs No. 15 & 16- Looking to the west. Observed the topography of the area which is coming down to the southeast. Any water or leachate barrier are observed along this area. Leachate Zone Z-1

Photographs No. 17- Looking to the northwest. After a heavy rain event occurring a day before our visit. Stagnant waters mixed with leachate was observed along this zone of the landfill. This is part of Leachate Zone Z-1

Photographs No. 18 & 19- Looking to the north. Leachate Zone Z-2 which is closed to the area facing the Luis Peña Canal. Any water runoff control was observed along this zone creating the possibility of leachate migration to the Reserve. The leachate leakage was observed very clearly in Photo No. 17 below.

Photographs No. 20 & 21- Looking to the north and west, respectively. Leachate Zone Z-2

Photographs No. 22 & 23- Looking to the west. Leachate Zone Z-3. This is the lower boundary of the landfill. Superficial leachate is observed at this temporary garbage deposit area.

Photographs No. 24 & 25- Looking to the west to the Luis Peña Canal from the top of the landfill. Cayo de Luis Peña is observed at the distance.

Photographs No. 26 & 27- Looking to the southwest from the top of the landfill. Vieques Island is observed at distance.

Photographs No. 28- Looking to the south. A rear-loaded garbage truck property of the Municipality of Culebra.

REFERENCES

1. “Declaración de Impacto Ambiental, Ampliación del Vertedero Municipal de Relleno Sanitario de Culebra, Puerto Rico”, DIA FINAL, Marzo 1992, by ABCaragol & Assoc.

2. “Geotechnical Engineering Report and Subsurface Exploration Program Culebra Sanitary Landfill Punta Bahia Tamarindo Culebra”, dated March 14, 1991, by Geopractica, Inc.

3. “Geotechnical Engineering Report (Addendum Note No.1) Subsurface Exploration Program Culebra Sanitary Landfill Punta Bahia Tamarindo Municipality of Culebra”, dated February 19, 1992, by Geopractica, Inc.

4. “Plan de Monitoreo y Rastreo Facilidades del Vertedero Municipal de Culebras”, by Alchem Laboratory

5. “Environmental Engineering”, Peavy/Rowe/Tchobanoglous, McGraw and Hill

6. “Options for Managing Municipal Landfill Leachate: Year 1 Development Of Iron-Mediated Treatment Processes”, January 2006, by James D. Englehardt, Report #0432024-06, State University System of Florida