ECOTROPICOS, Vol. 6 (1): 10-21. 1993
Sociedad Venezolana de Ecología

ORIGIN OF SEDIMENTATION AND ITS EFFECT ON THE CORAL COMMUNITIES OF A VENEZUELAN NATIONAL PARK

ORIGEN Y EFECTOS DE LA SEDIMENTACION SOBRE LAS COMUNIDADES CORALINAS DEL PARQUE NACIONAL MORROCOY, VENEZUELA

David Bone*, Freddy Losada* and Ernesto Weil**

* Departamento de Biología de Organismos, Universidad Simón Bolívar, Apartado 89000, Caracas 1080, Venezuela.
** Department of Zoology, University of Texas, Austin, TX 78712, USA.

ABSTRACT

Before 1974, the coral communities of the National Park of Morrocoy, NW of Venezuela, were subjected to several man-made disturbances brought about by an uncontrolled increase in tourism and related activities. In May, 1974, the area was decreed National Park by the government. Despite all the protective measures, the damage suffered by some reefs has increased since then. To quantify this situation several structural parameters of four reefs with healthy and damaged comunities were compared. A damage index was calculated, which measured the proportion of coral mortality in all reefs. From all parameters, the damage index was the most sensitive to the deterioration of the reefs. Sedimentological and mineralogical parameters from sediments samples of different reefs together with the analysis of Landsat satellite images, suggested that the extent and degree of the present damage in the northern reefs were mainly due to high sedimentation inputs resulting from erosion of land outside the boundaries of the Park.

Key words: Siltation, Coral communities, Venezuela, impact.

RESUMEN

Las comunidades coralinas del Parque Nacional Morrocoy, al NO de Venezuela, estuvieron hasta antes de 1974 sujetas al impacto de varios tipos de perturbaciones humanas, como consecuencia de un incontrolado incremento del turismo y actividades relacionadas. En mayo 1974, el área fue decretada Parque Nacional por el gobierno. A pesar de todas las medidas proteccionistas implementadas, el deterioro de estos arrecifes se ha incrementado desde entonces. Para cuantificar esta situación, se compararon varios parámetros estructurales en 4 arrecifes ubicados en comunidades dañadas y sanas. Se calculó un índice de daño, el cual mide la proporción de coral muerto en todos los arrecifes. De todos los parámetros usados, el índice de daño fue el más sensible al deterioro de los arrecifes. El análisis de parámetros sedimentológicos y mineralógicos de muestra de sedimentos, provenientes de diferentes arrecifes, unido a imágenes del satélite LANDSAT, dieron evidencias de que la extensión y grado de deterioro actual en algunos arrecifes, se debe principalmente, a aportes masivos de sedimento como resultado de procesos erosivos continentales en zonas ubicadas fuera de los límites del Parque.

Palabras claves: Sedimentación, Comunidades coralinas, Venezuela, impacto.

INTRODUCTION

Siltation can be the result of natural processes such as heavy rainfall and river drainage, or of human activities, such as dredging and poor land management. Natural erosion can enhance ocean productivity, but in excess, sedimentation can cause the destruction on coral communities (Johannes 1975, Pastorok and Bilyard 1985, Rogers 1990).

Sedimentation and sediment resuspension have been considered important factors affecting the distribution and abundance of coral species (Marshall and Orr 1931, Goreau and Wells 1967, Loya 1976), as well as recruitment (Johannes 1972, Lasker 1980), growth (Marshall and Orr 1931, Dodge et al. 1974, Dodge and Vaisnys 1977, Bak 1978) and mortality (Aller and Dodge 1974, Lasker 1980). However, it is well known that corals have several self-cleaning mechanisms that permit them to eliminate a certain amount of sediments deposited on their tissues (Yonge 1963, Hubbard and Pocock 1972, Bak and Elgershuizen 1976, Schuhmacher 1977). The efficiency of this sediment rejection varies for different coral species and depends on sediment size and type (Hubbard and Pocock 1972, Bak and Elgershuizen 1976, Lasker 1980).

Many coral reefs are found to be flourishing in turbid water. The existence of these communities in such conditions does not always imply that they are in a state of deterioration (Roy and Smith 1971), but any disturbance which causes a high sedimentation rate may overwhelm the self-cleaning capacities of even the most efficient corals, causing their death and leading to the decline of the community (Brock et al. 1966, Dodge and Vaisnys 1977, Bak 1978, Rogers 1983, 1990).

Erosion has considerable been increasing due to a lack of land management and river drainage has carried the products of this erosion into the sea. The effects of this kind of disturbance on coral communities have been documented elsewhere (Johannes 1975, Dollar and Grigg 1981, Corte's and Risk 1985), and since it usually has prolonged action on very large reef areas, the effects could be devastating.

During the last two decades, the coral communities of the National Park of Morrocoy, located in the northwest of Venezüela, have been affected by different kinds of man-made disturbances. Weiss and Goddard (1977) have reviewed the chronology of the main events which have damaged the northern reefs of the Park, until 1973. They reported on a series of changes which occurred in the main town of the area, Chichiriviche, a former fishing village that is now a tourist-centered town included in the Park. From 1957 to 1964 a cement plant, a water tank and pipeline, and an asphalt road that connects the town with the coastal highway, were constructed. According to the authors, these changes brought about a human population explosion and an increase in tourism and related activities, which affected not only the mainland but also the keys located near the coast of Chichiriviche.

Towards the end of the 60's the reefs began to be affected by several kinds of man-made disturbances, such as construction of houses and docks and the disposal of garbage, sewage and other materials into Chichiriviche Bay. From all these, Weiss and Goddard (1977) considered that sewage pollution caused the most damage.

The decade of the 70's began with the spread of buildings to all existent keys of the area and to many shoals, sand banks and reef flats. In May, 1974, the area was decreed National Park by the Venezuelan government. The demolition of all constructions on the keys and beaches was ordered that year and completed the next. Any further development of the coastal towns included within the Park was prohibited.

Despite these and other protective measures, the damage suffered by the reefs has increased since then. The reefs reported healthy by Weiss and Goddard (1977) in 1973, showed high dead coral cover values when first studied by us in 1979. Other reefs of the northern part of the Park had obvious symptoms of deterioration such as high dead coral coverage and the smothering of many living colonies by sediments (Bone 1980).

In this paper, we present evidence to suggest that the extent and degree of today's damage are mainly due to a high sedimentation process which began around 1972 and has increased since then. This recent kind of man-made disturbance has its origin on the mainland as a serious erosion problem resulting from bad management of agricultural land. The erosion products have been carried into the Park waters by the run-off of several rivers and the action of marine coastal currents.

METHODS

Four reefs were selected for this study according to their distance from the two main centers of human activities in the Park, the towns of Tucacas and Chichiriviche. Cayo Muerto and Cayo Sal, the most northern reefs, are located near Chichiriviche, whereas Cayo Pescadores and Costa de los Muertos are among the farthest apart from the two main population centers (Fig. 1). To sample each reef, underwater line transects perpendicular to the coast line were laid down using 50 m plastic measuring tapes. Three to eight transects, depending on the size of the reef, were laid parallel to each other with a separation of 25 m. The tape touched the corals on many points, and whenever possible, followed their contour. In places where the live corals were layered, all growth levels were considered. The method and criteria used to quantify the community structure were the same as those used by Loya and Slobodkin (1971) and Loya (1978).

For each underlying hermatypic colony along the tape we recorded species name and intercept length, as well as the condition of the colony (alive or dead). We also recorded other organisms such as zoanthids, sponges, seagrasses, algae and the type of substrate (sand, coral debris or bare coral skeleton). Only the most abundant benthic organisms, the scleractinian corals, were identified to species. Based on this information we calculated the following community structure paramaters for each reef: number of coral species, percentage cover for each species and Shannon-Weaver diversity index (H).

A damage index (d.i.) was calculated to express damage in terms of mortality of coral colonies. The total coral mortality on each transect Mj was first calculated by the equation:

$$Mj = \frac{Mi}{Mi + Li} \quad (1)$$

where Mi is the dead coral cover (i.e. denuded areas where coral morphology was still obvious or completely eroded, but not colonized by benthic invertebrates, in meters) for the species i; Li is the living cover (same units) for the coral species i; and n is the number of species present in the transect. Then the average coral mortality on transects monitored on the reef, M, was calculated by:

$$M = \frac{Mj}{N} \quad (2)$$

where N is the total number of transects.

The natural mortality, K, caused by natural events other than man-made disturbances or catastrophic events, was assumed to be equal to the one calculated by equations (1) and (2) for the control reef transects. Line transects from two other reefs, Playuela and Playa Caimán (Fig. 1), also selected because of their location relatively far from Tucacas and Chichiriviche, were sampled to calculate the damage index on relatively undisturbed reefs. Finally the damage index, which fluctuates between zero (no damage) and 1 (total damage), is the proportion of coral dead cover minus the natural mortality. The index is obtained by the equation:

$$d.i. = M - K \quad (3)$$

Community structure parameters were compared among the four locations using Kruskal-Wallis nonparametric test. When significant differences were found, a Mann-Whitney test was performed to determine differences between disturbed and undisturbed locations (Hollander and Wolfe 1973).

Sediment analysis

Samples of sediments were taken from the bottom of the fore-reef slope of each of the four selected reefs using plastic cores which were manually buried into the bottom to a depth of about 20 cm. Four cores forming the corners of a 4 m^2 were pooled in one sample.

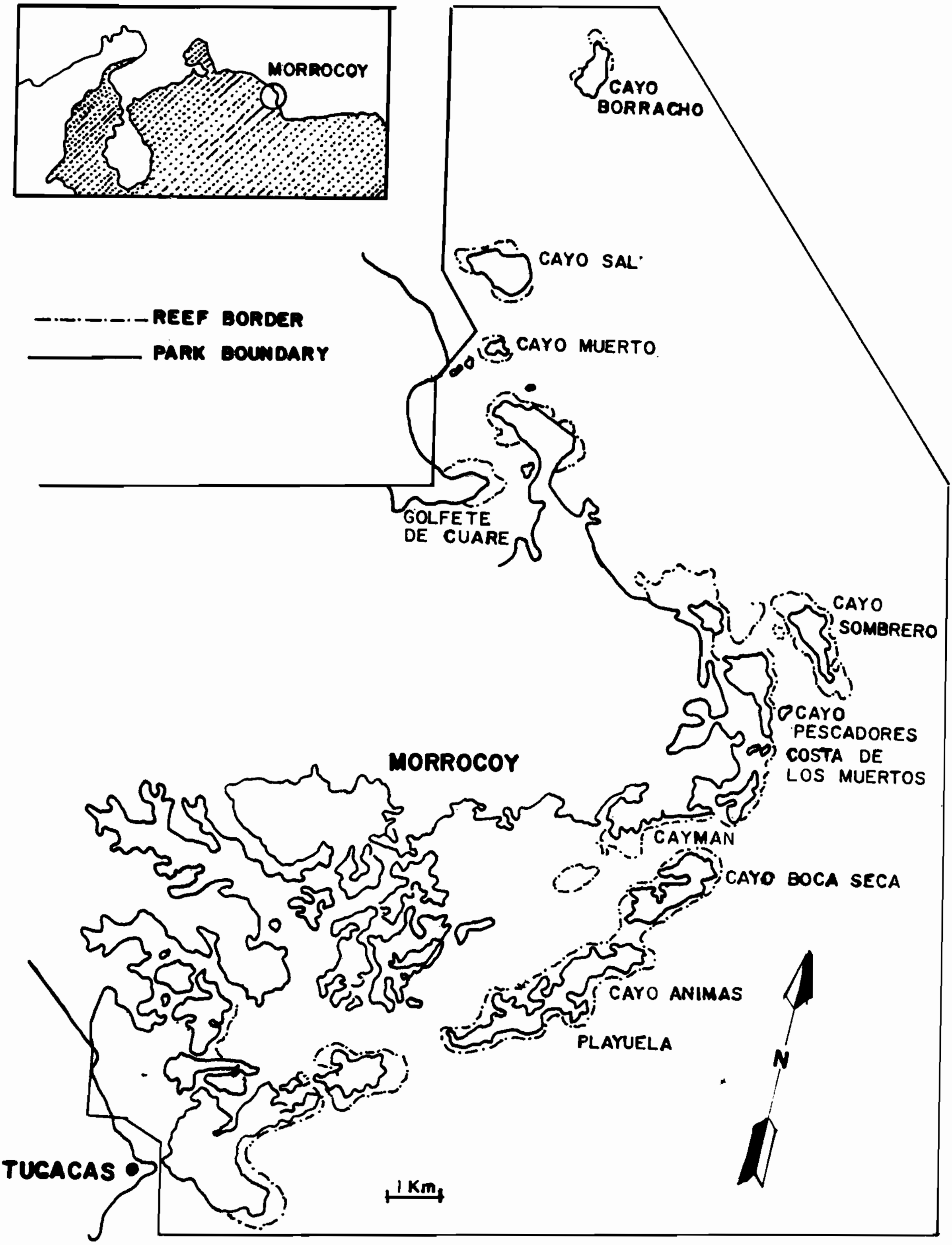

Figure 1. Parque Nacional Morrocoy, showing the location of the sampling sites.

Samples were analyzed for granulometric composition and x-ray diffraction in order to establish their probable origin by their mineralogical composition. They were dried in an oven at 50°-60°C during 24 hours and homogeneized. A subsample of a 100 g was then washed with water to separate the silt-clay fraction (<0.063 mm) from the sand-gravel fraction (>0.063 mm). Once separated, the two fractions were dried under the same previous conditions and weighted. The sand-gravel fraction was treated with 30% HCl to eliminate the carbonates and weighed again. Before the x-ray diffraction analysis, the organic matter of the silt-clay fraction was eliminated by oxidation with hydrogen peroxide according to a procedure described by Roa and Berthois (1975). Samples were run under a Phillips high-intensity x-ray diffractometer (1800 W, 60KV).

RESULTS

Table 1 shows the proportion on the coral natural mortality, K, relative to the total coral cover calculated from seven control transects which we assumed to be caused by natural events acting on the Park, such as predation, disease, etc. The values of K fluctuated between 0.13 and 0.34 with an average of 0.25. This means that one-fourth of the total coral cover of each control transect was dead. Although the control transects were run on reefs far from the main centers of human activities, the average value of 25% should not be considered the natural mortality for all healthy reefs, as percent dead coral on any reef is extremely variable.

Table 2 is a summary of several structural parameters of the coral communities in the reefs we studied. The different substrates, mainly sand and coral debris, occupied from 25 to 50% of the total transect cover. Hermatypic corals occupied from 20 to 50% of the total cover and other benthic organisms, such as algae, the seagrass *Thalassia testudinum*, sponges, zoanthids and octocorals, from 30 to 45% of the cover.

The reefs of Cayo Pescadores and Costa de los Muertos, located far from the main centers of disturbances, showed the highest values of H' diversity index (0.78 and 0.86 respectively) and the lowest values for the damage index (0.09 and 0.19), whereas Cayo Sal and Cayo Muerto, had the lowest H' values and the highest d.i.

Differences of the diversity values among localities were found to be nonsignificant (Kruskal-Wallis, $H = 6.35$, $p > 0.05$), but the values for number of species and damage index were statistically significant (Kruskal-Wallis, $H = 10.05$ and $H = 12.60$

Table 1. Natural mortality (k) (proportion of the total coral cover found dead) of hermatipic corals in control transects on healthy reefs.

Locality	Number of Transects	Natural Mortality (k)
Cayo Pescadores	2	0.22
		0.16
Playuela	2	0.32
		0.30
Caimán	2	0.21
		0.13
Costa de los Muertos	1	0.34
Mean value:		0.25±(0.81)

respectively, $p < 0.05$). The number of species was significant lower in the reefs from the Chichiriviche area (Mann-Whitney test), while the damage index was significantly higher.

If we compare the mortality of the most abundant hermatypic coral species in the studied reefs, the differences are even more striking. The two commonest species, *Acropora palmata* and *Diploria strigosa*, showed the highest mortality on the reefs closer to Chichiriviche (Table 3). Species like *Colpophyllia natans* and *Montastrea annularis*, also present in most localities, invariably showed higher mortalities in the reefs closer to Chichiriviche. These results indicate that the healthier reefs were those farther from the two main centers of human activities within the Park.

Tables 4 and 5 show the results of sediment analysis. As expected for this kind of environment, carbonates were the main constituent of sediments in all reefs but their percentage in the samples decreased towards the Chichiriviche area. The silt-clay fraction increased its percentage towards the same area (Table 4).

Table 2. Mean values of various community structure parameters for the studies reefs (standard deviation in parentheses).

Variables	Cayo Muerto	Cayo Sal	Cayo Pescadores	Cayo Los Muertos
Number of Transects	4	6	6	8
Transect Length (m)	75.0 (7.4)	111.6 (15.5)	124.5 (26.0)	116.7 (36.2)
Number of species	8 (1.3)	10 (1.7)	11 (1.5)	13 (5.1)
Range of number of species	7-10	8-13	10-14	6-12
Living coral cover (%)	26.5 (3.9)	19.9 (12.8)	33.0 (6.9)	15.8 (6.9)
Living coral (%) (other organism)	38.0 (5.8)	52.4 (4.8)	24.2 (6.2)	36.5 (11.9)
Substrate cover (%)	36.3 (5.4)	27.4 (11.4)	41.7 (9.6)	47.0 (9.6)
Diversity (H')	0.68 (0.8)	0.76 (0.7)	0.78 (0.1)	0.86 (0.2)
Damage index	0.27 (0.1)	0.31 (0.15)	0.09 (0.08)	0.19 (0.09)

Table 3. Relative dead coral cover of the ten most abundant species (in meters). Rank order within each location is given in parentheses.

Species	Cayo Muerto	Cayo Sal	Cayo Pescadores	Cayo Los Muertos
Montastrea annularis	5.15 (6)	2.53 (1)	1.97 (2)	0.96 (2)
Acropora palmata	5.25 (1)	2.17 (2)	1.47 (3)	1.71 (5)
Acropora cervicornis	-	-	-	1.12 (7)
Agaricia tenuifolia	-	-	3.74 (1)	5.16 (1)
Colpophillia natans	3.15 (2)	1.73 (5)	0.86 (7)	2.95 (3)
Porites porites	1.18 (5)	0.30 (9)	0.88 (6)	2.10 (4)
Porites astreoides	0.26 (10)	0.10 (12)	1.46 (4)	0.67 (9)
Diploria clivosa	1.63 (3)	0.84 (4)	0.26 (9)	0.57 (10)
Diploria strigosa	1.40 (4)	0.59 (6)	0.10 (13)	1.47 (6)
Millepora alcicornis	0.39 (7)	0.52 (7)	1.06 (5)	0.47 (12)

The analysis of most conspicuous minerals of the silt-clay fraction showed the presence of these minerals in all reefs but their proportion varied from reef to reef (Table 5). Samples from the Chichiriviche area had a higher content of quartz and feldspars and a lower content of muscovites. The presence of these minerals indicates their continental origin and suggests an important influence of river drainage on the Park waters.

Table 4. Percent silt-clay fraction and carbonate content in sediment samples collected from the studied reefs.

	Cayo Muerto	Cayo Sal	Cayo Pescadores	Cayo Los Muertos
Silt-clay fraction (%)	20.0	10.0	8.0	5.3
Carbonate content (%)	80.0	90.0	92.0	94.5

Although the silt-clay fraction did not represent more than 20% of the bottom sediment samples at any reef, many coral colonies were found smoothered by a type of sediment which had the same grain size than the silt-clay fraction. We also believe that the water with high turbidity found in the Chichiriviche reefs was mainly due to the resuspension of this type of sediments.

Figures 2 and 3 are drawings based on LANDSAT satellite photographs of the distribution of sediments carried into the sea by the drainage of several rivers outside the Park boundaries. The run-off of Rio Tocuyo and other small tributaries causes the northern plume of sediments which is recently affecting the reefs of the Chichiriviche area. The run-off of rivers Aroa and Yaracuy causes the southern plume of sediments reaching the Tucacas area. The reefs of Pescadores and Costa de los Muertos are less affected by this sedimentation.

Table 5. Constitutent minerals of the silt-clay fraction in sediment samples collected from the studied reefs.

	Cayo Muerto	Cayo Sal	Cayo Pescadores	Cayo Los Muertos
Quartz	22.0	24.0	16.0	16.0
Kaolin	0.5	12.0	0.6	0.6
Montmonllonites	0.5	0.1	0.3	0.3
Mica and Illites	0.2	16.0	0.7	0.7
Muscovites	0.1	0.5	17.0	17.0
Feldspars	1.3	1.8	0.3	0.1

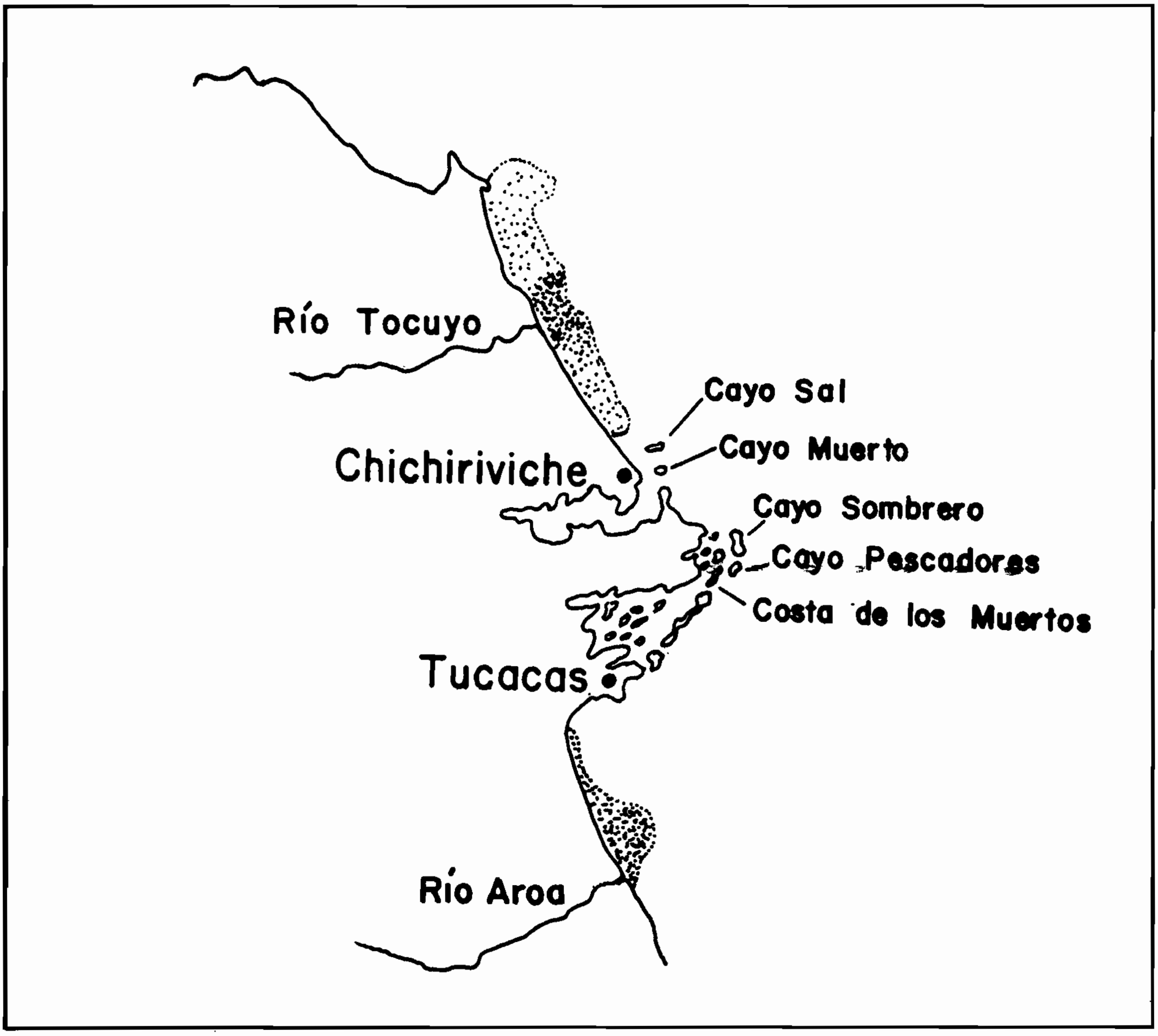

Figure 2. Drawing of a LANDSAT satellite photograph taken in March 10, 1975, showing sediments distribution outside the Park boundaries.

DISCUSSION

The presence of the silt-clay fraction in the sediments of all reefs studied and its mineralogical composition clearly indicate the influence of river drainage on the Park. The highest proportion of this fraction found in Cayo Muerto and Cayo Sal and the satellite photographs which show the sediment plume reaching those reefs suggest that the northern part of the Park is the most affected by the sedimentation process.

Recent studies of the rivers Yaracuy, Aroa and Tocuyo have concluded that natural erosion has been accelerated by human activities (Flores and Guilarte 1971, Gil 1975, Castillo 1975). Gil (1975) and Castillo (1975) have suggested that bad management of agricultural land, such as an irrational cutting of timber and forest fires along the river banks, have reduced the vegetation cover which protected the banks from erosion.

Hernández et al. (1967) have studied the characteristics of sediments and the volume of suspended solids in the river Tocuyo. They reported that 98% of the sediments in suspension were of the silt-clay fraction with a mean diameter of 23 u. Our

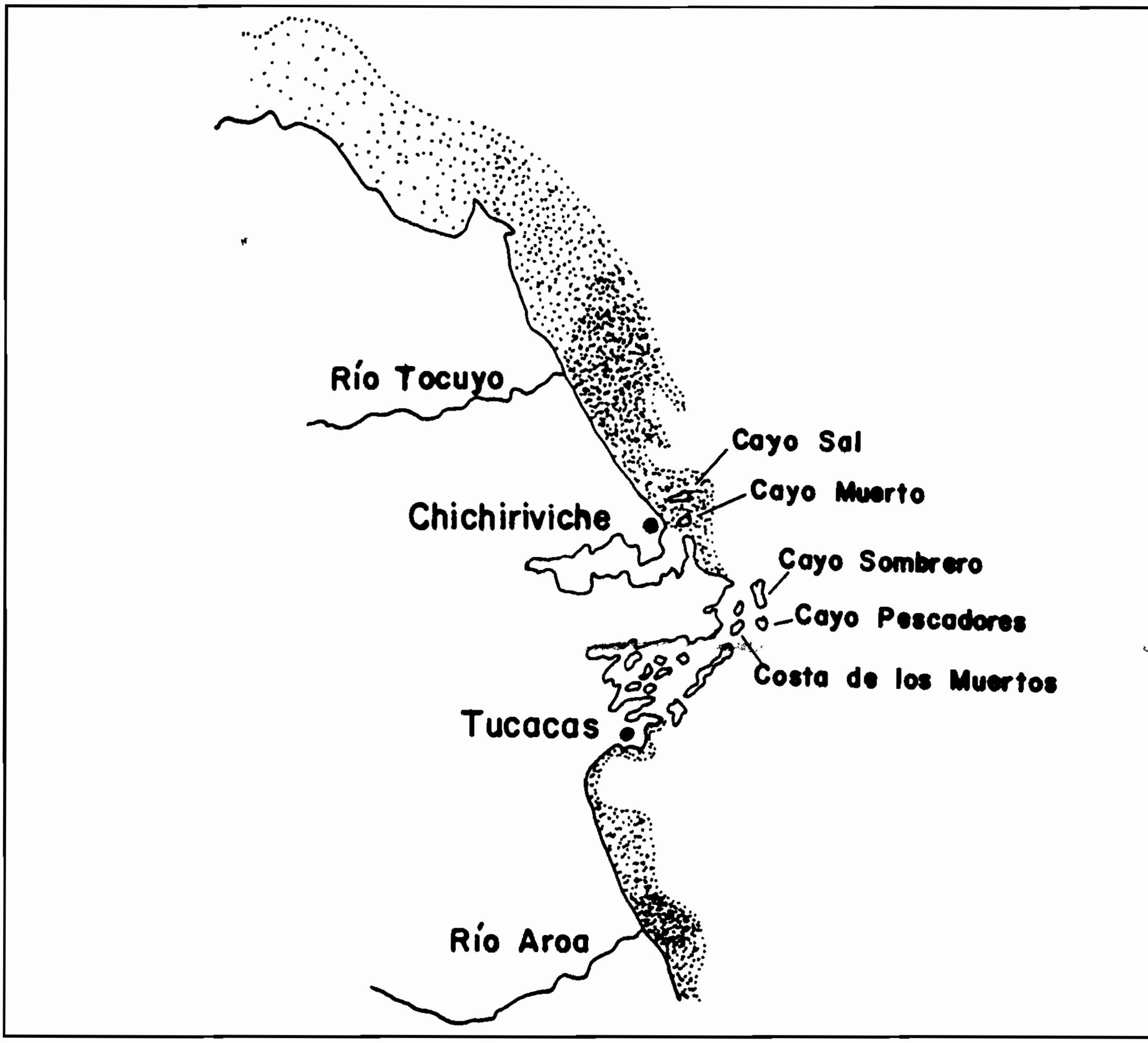

Figure 3. Drawing of a LANDSAT satellite photograph taken in March 21, 1978, showing sediments distribution outside the Park boundaries and inside it's northern end.

results still show a relatively high percentage of this fraction in the sediments of the northern reefs, approximately 10 km south of the Tocuyo river mouth.

The reefs of Cayo Sal, Cayo Peraza and Cayo Pelo'n, reported by Weiss and Goddard (1977) as normal in 1973, appeared severely damaged during our sampling in 1979, although the demographic pressure has ceased in 1974 when the area was decreed a National Park. We think that the extension of stress over those reefs and their actual situation is mainly due to high sedimentation rather than sewage pollution or other factors (e.g. disease) for the following reasons. First, the main currents are NE-SW during most of the year and this would have carried the sewage towards the Golfete de Cuare, only affecting the communities of that area. Second, if sewage is responsible for the damage, we have to assume there has been a significant increase in the human population of the area, which has not happened. Other factors, such as disease (e.g. white band disease), were not reported for nearby areas, where healthy reefs still flourished (Weiss and Goddard, 1977).

Within the Park, we have observed the

sedimentation phenomenon on several occasions with different intensity. Chichiriviche residents have communicated to us that the phenomenon happens from 4 to 5 times a year, being very intense during rainy season. Their opinion is that the sedimentation has increased in intensity in recent years. A similar situation was reported by Corte's and Risk (1985) for the coral reefs at Cahuita's National Park, Costa Rica. These reefs have undergone heavy siltation effects from nearby river drainages. Considerable mainland deforestation for lumber and agriculture has taken place for the past 30 years along river basins. Although the reefs may not be directly comparable to ours, their overall findings were similar: (1) reduced live coral coverage; (2) reduced species diversity and (3) high amounts of terrigenous materials in the reef sediments. They also report low coral growth rates and low recruitment rates. Deforestation and subsequent increased siltation seems to be common problems throughout the Caribbean.

Hubbard and Pocock (1972) tested 26 species of scleractinian corals from Florida for their abilities to reject sediments from less than 0.006 mm to 2.0 mm of grain size. They found that all corals remove silt by ciliary action and that with the exception of *Meandrina meandrites* and *Solenastrea hyades*, all species tested had moderate to strong capacities to reject sediments smaller than 0.125 mm. This means that most of the Caribbean hermatypic corals would be able to survive the stress of low or moderate sedimentation of mainland origin. The high mortalities we found for some species in the most turbid reefs is an indication that the sedimentation on these reefs could be very severe at least during rainy season.

Loya (1976) compared the community structure of two reefs in Puerto Rico stressed by different amounts of water turbidity and sedimentation. Coral species diversity (H'=2.2) and living cover (79%) were greater in the reef with less turbidity and sedimentation. On the other hand, the reef developing in very turbid waters and high sedimentation environment had a lower species diversity (H'=1.8) and lower living cover (30%). The most abundant species were the most efficient in removing sediments. Our results showed a similar pattern, but when we compared the community structure of Cayo Sal, a deteriorated reef with high turbidity, with Cayo Pescadores, a healthy reef with less turbidity (Table 2), we found that the only parameters which could clearly express the differences between the two reefs were the damage index (the percentage of dead cover over the natural mortality of control reefs) and the number of species. Thus, species diversity and living coral cover may not necessarily be different in two reefs with very different levels of turbidity and sedimentation.

When a reef community is disturbed, the original ecological conditions are altered. The eventual recovery of the reef, which requires recolonization of bare areas by settlement of larvae and regeneration of partially damaged colonies, could take several decades, depending on the type of disturbance and degree of damage. Johannes (1975), Endean (1976) and Pearson (1981) have published extensive review on these aspects. Thus, the destruction of the reef is not just a change on its physical appearance but also a change in biological interactions which may imply emigration of many organisms associated to the reef, including fishes and crustaceans (Gunderman and Popper 1975).

ACKNOWLEDGEMENTS

The authors like to thank Dr. Pedro Roa Morales, Dr. Luis Bulla, and one anonymous reviewer for reading and improving the manuscript, Danilo and Elsa Cobo for their help and friendship throughout this work, and Victoriano Roa for drawing the figures. This study was partially financed by CONICIT (Grant No. 496 - 111 and Project No. S1 - 0679).

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