GEOLOGICAL AND ENVIRONMENTAL REMOTE SENSING LABORATORY
Department of Geology
University of Puerto Rico at Mayaguez

Final Report:
Temporal Changes of La Parguera Reefs as Detected with Remote Sensing

Ketlyn A. Rodríguez González
802-00-6394
Advisor: Dr. Fernando Gilbes

Abstract

The purpose of this research is the use of Remote Sensing to determine changes through time of the distribution of the coral reefs of La Parguera. For this, three aerial photograph (1936, 1977, 1999) and two images (CASI, IKONOS) of the area were processed using IsoData, K-Means and Minimum Distance methods. IsoData and K-Means results were not the best. The Minimum Distance had the best results and changes through time in the distribution of the reefs are detected. Remote Sensing, then, can be used to detect changes of the distribution of the coral reefs of La Parguera.

Introduction

Coral reefs are considered to be the rain forest of the oceans due to its biodiversity. Around 25 % of the world's marine species are located in these ecosystems (CNN, 1997). Due to anthropogenic and natural causes, coral reefs are in jeopardy. Human activities such as fishing, sailing, costal development, agriculture, deforestation, among others, are responsible for most of the coral reefs degradation (CoRIS, 2004).

Fishermen exploit coral reefs because of the diversity found in them. This over fishing causes the overgrowth of sea grass. Since there is no sufficient fish to eat it, coral reefs get covered with algae and can not receive enough sunlight needed for photosynthesis of the *Zooxanthellae* that live in them and provide color and additional food for the corals (Ocean World, 2004). Boats that pass by these ecosystems can affect them by breaking them apart and by spilling their fuels, polluting the area. Construction of hotels and tourist's developments causes runoffs, sedimentation and sewage spills. Eventually these end in the ocean bringing high amounts of nutrients and turbidity, decreasing the sun light that gets into water and causing eutrophication (overgrowth of algae in water due to the excess of nutrients causing the go away of the *Zooxanthellae* from the coral because they do not receive sufficient light for their photosynthesis). Corals then bleach and can die (CoRIS, 2004).

Agriculture and deforestation have more or less the same effects on them. The chemicals needed for maximum cultivation go to the coasts when it rains and eutrophicate the areas. When there is a clear up of green areas, the land that used to be covered with grass, trees, plants, etc., is no more protected or stable. Rain falls and the unprotected terrain mixes with the water carrying sediments and nutrients to the coast.

Natural causes such as hurricanes, greenhouse gases, low tide, etc., also affect negatively the coral reefs. The drastic rains, involving hurricanes, bring huge quantities of sediments that end in the oceans and powerful waves, which can break corals apart. The greenhouse gases effect warms the water. *Zooxanthellae* can not live in such temperature conditions and they leave the corals. Then corals suffer from bleaching. Lowering in the tide rise can also cause bleaching. Coral reefs are exposed receiving direct rays of light that expel the Zooxanthellae (CoRIS, 2004).

Corals reefs around the world are affected by these stresses and Puerto Rico's coral reefs are no exception. In this research the area of study is La Parguera in Lajas. The coral reefs in this location are considered to be the healthiest of coastal Puerto Rico, because of their high abundance of living coral. This is caused by some factors (Bruckner, A., Carlo, M., Morelock, J., Ramírez, W., 2001).

Mangroves are natural barriers that prevent sediments from being carried by the run offs directly to reefs. There are no close rivers that could cause eutrophication and/or a lowering of the sunrays into the water column due to sediments. These help to maintain certain healthy status in the coral reefs. Anyhow, they are being affected by the rapid urbanization that increases the sedimentation in rainy seasons, bringing nutrients from the terrain and the sewage systems, increasing the growth of sea grass. Hurricanes also have been contributing to their degradation due to the excess of sediments and their destructive waves (Bruckner, A., Carlo, M., Morelock, J., Ramírez, W., 2001). Having all these factors in mind it is possible to come up with some ideas for a research that could help to determine changes in the reefs of La Parguera.

Remote sensing can not determine which are exactly the reasons for the changes of the reefs, but it is possible to infer what may have cause it by establishing the relation of the urban development with the reefs changes. The sensors can detect construction and development of the area (land use and land cover changes); and we could find out if these are being increasing by comparing the images and photos. The urban development can cause run offs with sediments and nutrients eutrophicating the reefs. This eutrophication may cause changes in the distribution ecosystem.

Objectives

This research is concentrated in the study of the coral reefs of La Parguera from 1930's to present. Images of these reefs taken by IKONOS, CASI (Compact Airborne Spectrographic Imager), and three aerial photos (1936, 1977 and 1999) were analyzed to see if there are visible and spectral changes in the reefs. It tries to determine changes through time of the distribution of the communities that compose the ecosystem. The research will find out if several remote sensors can easily capture these changes and which is the best sensor for it. This will help to select the right tool for future studies. Also, it pretends to determine whether or not there are noticeable distribution differences in the spectral response in the reefs between the images and photos, and which of the unsupervised (IsoData and K-Means) methods used to detect the changes are similar to the supervised method. Therefore, the hypothesis of my work is that remote sensing techniques can be used to detect the distribution changes of coral reef's communities through time.

Methodology

Three images of La Parguera, one from IKONOS without being pre-processed (Figure 5), the other one a de-glinted IKONOS (figure 6), CASI (Figure 4) and aerial photograph from 1999 (figure 3) were facilitated by the GERS (Geological and Environmental Remote Sensing Laboratory). Aerial photographs from 1936 (figure 1) and 1977 (figure 2) were provided by ¨La División de Fotogrametría de la Autoridad de Carreteras¨. ENVI (Environmental of Visualization Images) was the program used for the processing of the images and photos.

Table 1:IKONOS and CASI sensor descriptions

Sensor	Orbit	Resolution	Bands
IKONOS	Sun synchronous, every 98 minutes	High spatial resolution (1m, 4m)	Panchromatic, multispectral
CASI	Airborne combines the best of aerial photography and satellite imagery.	High spatial resolution (5m)	Hyperspectral 288 channels (400- 915 nm)

Figure 1: Aerial photograph of 1936

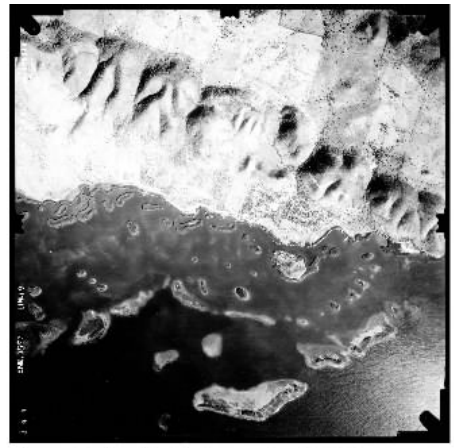

Figure 2: Aerial photograph of 1977

Figure 3: Aerial photograph of 1999

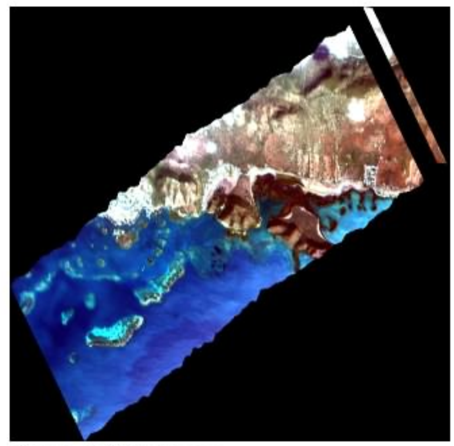

Figure 4:CASI image

Figure 5: IKONOS image

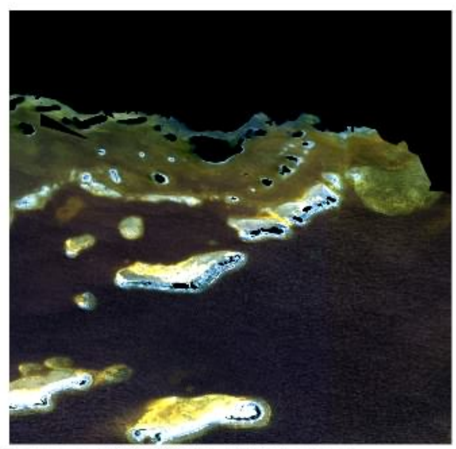

Figure 6: IKONOS de-glinted image

For the purpose of the investigation, IKONOS and CASI images with three aerial photos of La Parguera reefs were processed using ENVI. There was a need to use a de-glinted IKONOS image (figure 5) because the original one had sun glint problems that affected the outcome result of the unsupervised images, not letting to identify the real classification in the water. The aerial photos of different years (1936, 1977, and 1999) were compared in between and with the images (image interpretation) to determine visible changes of the reefs. Georeferencing and atmospheric corrections were performed. This is needed to have a better quality of the images and photos classification. The CASI image (figure 10) and the aerial photos (figure 7, 8 & 9) were georeferenced based on coordinates of the IKONOS image (figure 1), because it has the highest spatial resolution. The de-glinted image was not georeferenced, because it was already. Georeferencing consist in removing geometric errors and rectified to a real-world coordinate system (Decision Support, 2003). After the georeferenciation, they were re-sized using the subset application to have the same study area in all of them (figures: 11, 12, 13, 14,15 & 16).

Atmospheric corrections were done to correct atmospheric attenuation and some scattering effects to obtain a close estimate of a surface spectral radiance (CIS, 2004). For these atmospheric corrections the dark subtract method was applied to each of the images and aerial photos, except for the de-glinted IKONOS that already was pre-processed with the de-glinted method. Then, they were classified using supervised and unsupervised methods. Supervised classification is defined as the processes using sample of known identity to classify pixels of unknown data. The analysts have control of the data and they select the regions of interest (ROIs), which are the areas that are going to be classified to distinguish one object from the other. Minimum distance was the method used for this classification. It classifies using the ROI's closest pixels.

Unsupervised classification is defined as the identification of natural groups, or structure, within multispectral data (Introduction to Remote Sensing, 2002). The researcher does not directly control this classification. ENVI gives classes according to the similarities of the spectral response. With this method one class may represent several objects, meaning that the classification can not distinguish between one another. IsoData and K-Means were the unsupervised methods used, because they were the only methods available in the ENVI program. Unsupervised and supervised classifications were compared. After image processing, the data were analyzed using statistical procedures.

Forty points were selected for each of the photos and images to evaluate the changes through time in the different classes.

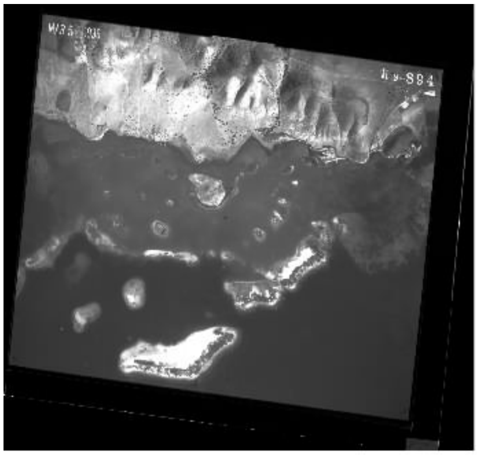

Figure 7: Georefereced aerial photograph of 1936

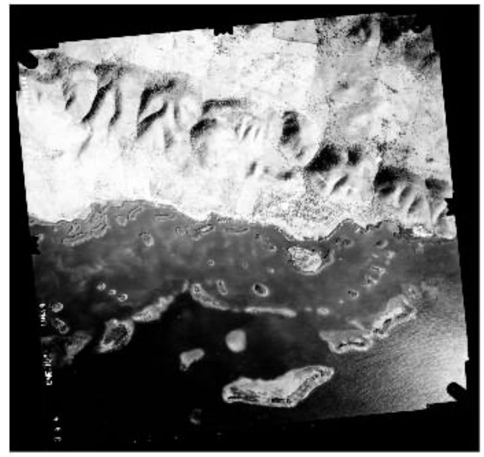

Figure 8: Georefereced aerial photograph of 1977

Figure 9: Georefereced aerial photograph of 1999

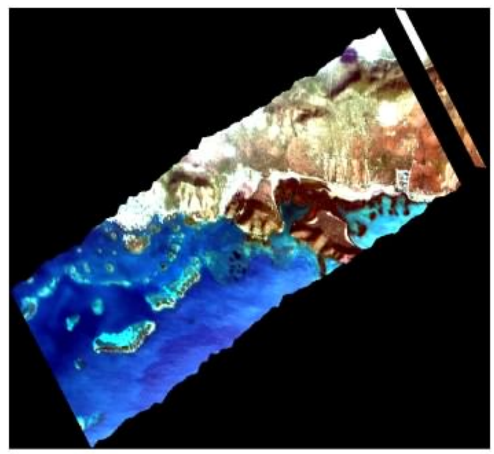

Figure10: Georefereced CASI image

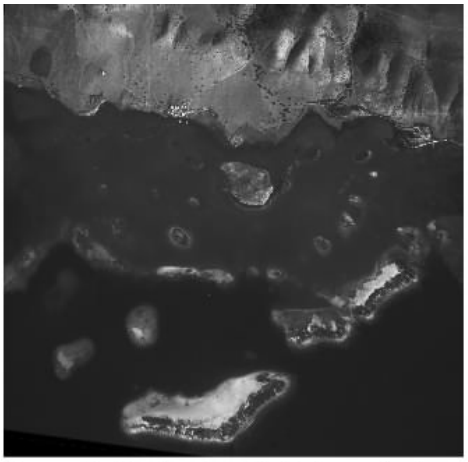

Figure 11: Re-sized aerial photograph of 1936

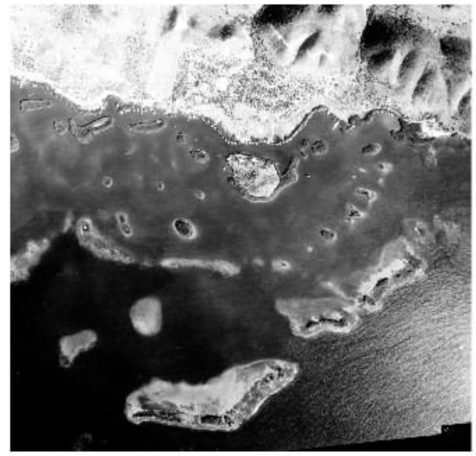

Figure 12: Re-sized aerial photograph of 1977

Figure 13: Re-sized aerial photograph of 1999

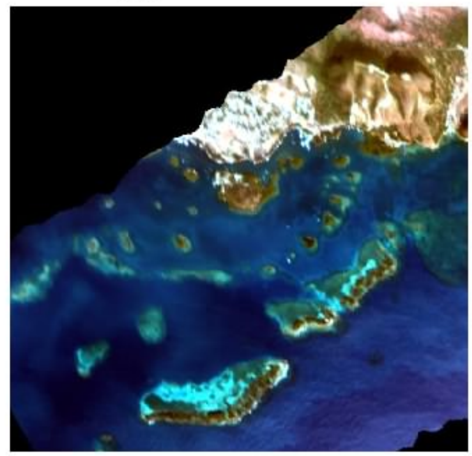

Figure 14: Re-sized CASI image

Figure 15: Re-sized IKONOS image

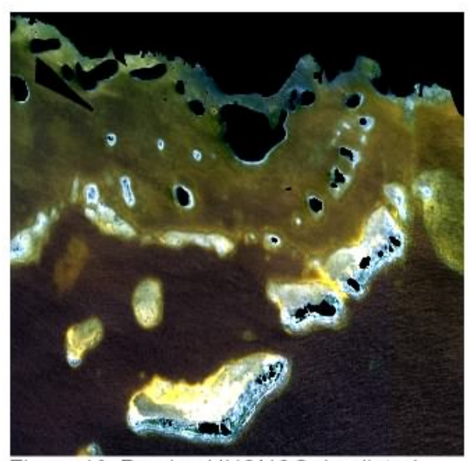

Figure 16: Re-sized IKONOS de-glinted image

Results and Discussion

I. Description for the aerial photographs and images

Dark subtract was used to remove the effect of the atmosphere that affects negatively the outcome classification of the images and photos. Comparing these images and photos (figures: 17, 18, 19, 20 & 21) it is possible to see changes. The most noticeable change is found in the main land. Urban development largely increased since 1936 until 1977, and from this year to 2001 (IKONOS image) such changes are less dramatic. There is no floating house in the coastal line in 1936, but in 1977 until the present they are found. The second most noticeable change is located in the coral reefs were the sand had been reduced and taken by the sea grass community. In the coastline, just north of Magueyes Island there is a wetland area in 1936 that have been reduced, specifically their water content. The amount of mangroves has increase in this area. These wetlands have been covered with houses, buildings, and roads since 1977.

Mangroves in general are not well detected in 1936, mainly because of the quality of the aerial photograph. This demonstrates the limitation of using black and white photos for this type of work. Areas with sandy bottom in 1936 were covered by mangroves in 1977 and until present.

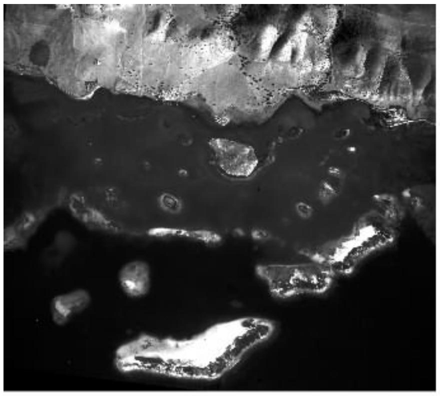

Figure 17: Dark Subtract aerial photograph of 1936

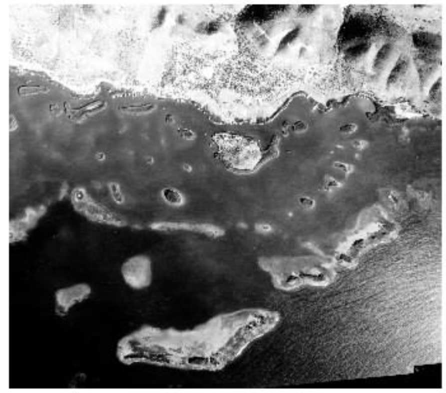

Figure 18: Dark Subtract aerial photograph of 1977

Figure 19: Dark Subtract aerial photograph of 1999

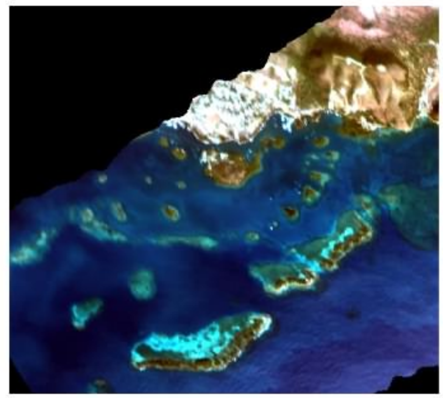

Figure 20: Dark Subtract CASI image

Figure 21: Dark Subtract IKONOS image

II. Supervised Classification

The supervised classification distributes the classes much better than the unsupervised methods. Although classes sometimes get confused with other classes, boundaries are better established. The small urban area of the 1936 photo can be distinguished and compared with the urban areas photos and images of the following years. The Minimum Distance method is adequate to determine the change in distribution of the urban development and it is clear that it have increased dramatically.

In almost all the photos and images the mangroves are well defined (figure: 22, 23, 24, 25, 26 & 27). The 1936 aerial photograph confronts problems distinguishing the mangroves areas, but the Minimum Distance method minimizes the problems and the mangroves are better identified. Mangroves are not good defined in the 1977 photo as it was with the unsupervised methods. For the 1999 photo mangroves tend to blend with shallow areas that were classified under the Mangroves class. The Minimum Distance is a good method to determine the changes in distribution for the mangroves of La Parguera reefs, because this classification shows that they have increased.

This classification does not significantly confuse sand with any other class as seen in the IsoData and K-Means methods. Comparing the classification it is clear that sand, sea grass and coral are well defined. Sand has been reduced; meanwhile the sea grass community has expanded. In the other hand, is difficult to determine if the coral community distribution has changed through time.

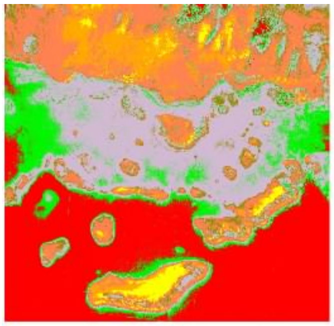

Figure 22: Minimum Distance of the aerial photograph of 1936

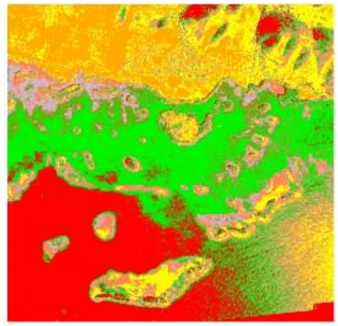

Figure 23: Minimum Distance of the aerial photograph of 1977

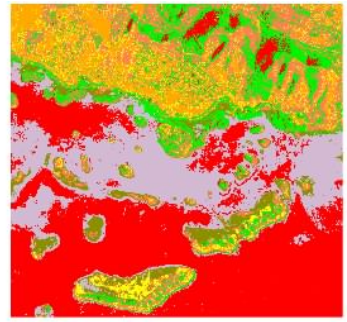

Figure 24: Minimum Distance of the aerial photograph of 1999

Figure 25: Minimum Distance CASI image

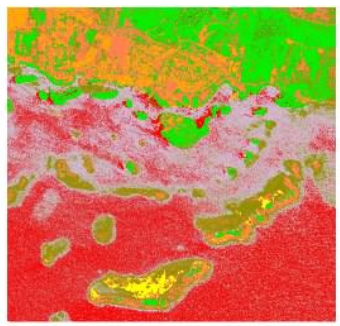

Figure 26: Minimum Distance IKONOS image

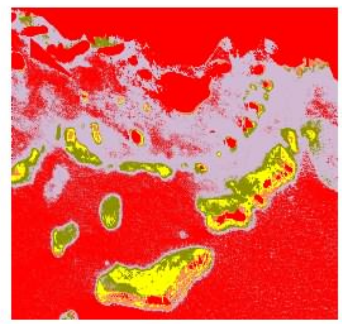

Figure 27: Minimum Distance IKONOSde-glinted image

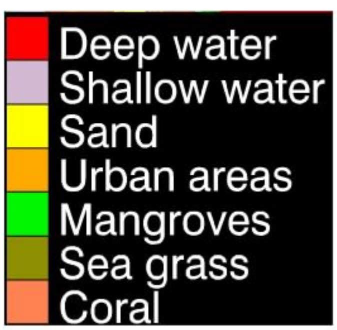

Table 2:Color interpretation for aerial photograph and images of Minimum Distance supervised classification						
Class	**Color**	**1936**	**1977**	**1999**	**CASI**	**IKONOS**
Deep water	Red	Deep water	Deep water, coral reefs, sea grass and mangroves	Deep water	Deep water and sea grass	Deep water
Shallow water	Thistle 2	Shallow water, sea grass, coral reefs and mangroves	Shallow water, sea grass, coral reefs and mangroves	Shallow water	Shallow water	Shallow water and sea grass
Sand	Yellow	Sand and urban areas	Sand and coral reefs	Sand and coral reefs	Sand	Sand
Sea grass	Yellow 3	Sea grass, coral reefs and shallow water	Sea grass, coral reefs and shallow water	Sea grass and shallow water	Sea grass and shallow water	Sea grass, coral reefs and shallow water
Mangroves	Green 1	Deep water and mangroves	Sea grass and mangroves	Shallow water, coral reefs and mangroves	Mangroves and coral reefs	Mangroves
Coral	Coral	Coral reefs, shallow water and sea grass	Coral reefs, shallow water and sea grass	Coral reefs, shallow water, mangroves and sea grass	Coral reefs, shallow water, mangroves and sea grass	Coral reefs and urban areas
Urban areas	Orange 1	Coral reef and sand	Urban areas and sand	Sea grass and shallow water	Urban areas	Urban areas and sand

III. Unsupervised Classification

The IsoData method gave 7 classes (figures: 28, 29, 30, 31 & 32) while the K-Means method gave 5 classes (figures: 33, 34, 35, 36 & 37) . These classes do not represent the same classes or colors used in the supervised classification. The distribution of classes using these methods depends on the spectral responses for each pixel in the photo or image.

The IsoData method classified the areas according to their similarities in the spectral response or brightness. Apparently, for this classification, classs 7 (maroon color) includes urban areas, areas with small amounts of vegetation, sand and coral. Urban development and areas with small amounts of vegetation are difficult to distinguish because they are producing the same spectral response. Comparing the photos and images (figures: 28, 29, 30, 31 & 32), it is noticeable that class 7 has extended in the main land, but is difficult to know if such increment is due to the urban development, the amount of vegetation, or both. Consequently, the method does not help to determine increments through the years in the urban development of La Parguera. Similar results are found with the sand and the corals. They live together and the unsupervised method does not differentiate them. Therefore, if there is an increment in the distribution of the corals community or the sand, it is difficult to detect it with the IsoData classification. It is noticeable that the distribution of this class has declined through the years, indicating that maybe the sand, the corals or both have being decreasing since 1936 to the present. Comparing with non-processed images and photos it is possible to infer that classification results are mainly produced by changes in sand distribution, especially decreasing in the keys through the years.

Mangroves are not well seen in the aerial photograph of 1936, because of the limitation confronted with the black and white photos. Consequently, the IsoData method did not make a good classification for it. The best classified mangroves are located in the main land and the color green (class 2) and blue (class 3) represent them mostly. They get confused with the blue of the shallow water, therefore is difficult to know their distribution. For the aerial photograph of 1977 mangroves are more defined and they stand out from the rest for having a greenish color and for having a red (class 1) shadow next to it. Mangroves are not defined in the 1999 photo, they tend to get confused with the cyan (class 5) and yellow (class 4) that also represents shallow water. For the CASI image something similar happens. Mangroves are not distinguishable from the rest. They tend to form part of the classes 4 and 5 that represents shallow water. IKONOS image present very distinguishable mangroves represented mostly with the color green. Determining changes through time in their distribution with this unsupervised method is not easy to achieve due to problems with the classification where mangroves were not distinguishable and tended to be confused with other classes.

Cyan (class 5), yellow (class 4) and magenta (class 6) represent sea grass in the keys in all images and photos. Sea grass could be confused with shallow water, but they are away from the sea grass, except for the CASI image. Making a comparison we could determine that the sea grass community distribution has been increasing and occupying the sand’s area. Thus, the most significant change in distribution through time provided by this classification in La Parguera is the changes in sea grass.

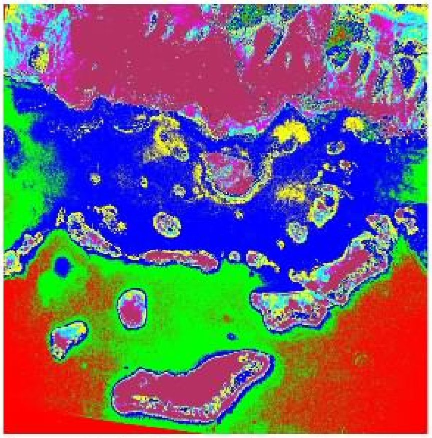

Figure 28: IsoData aerial photograph of 1936

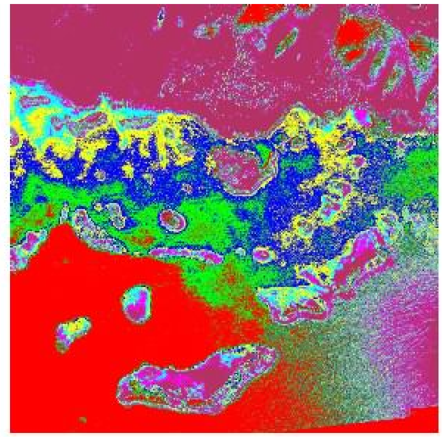

Figure 29: IsoData aerialphotograph of 1977

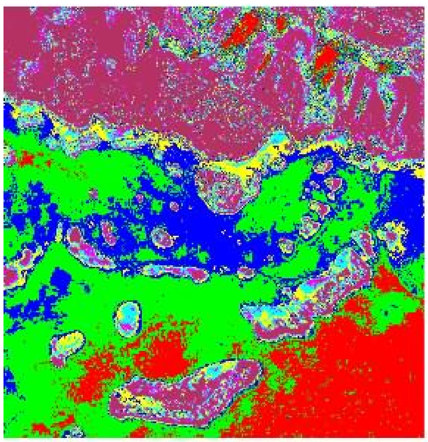

Figure 30: IsoData aerial photograph of 1999

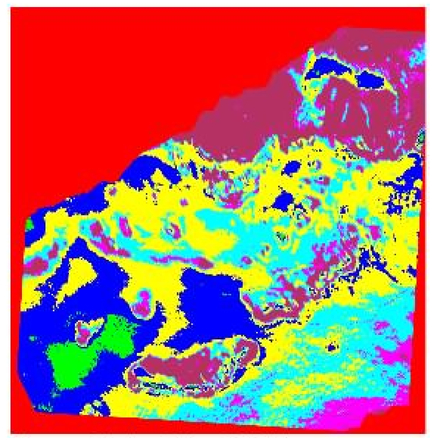

Figure 31: IsoData CASI image

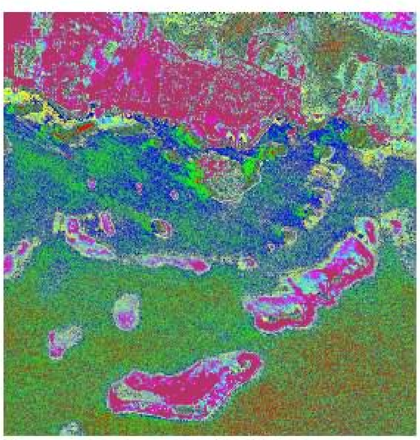

Figure 32: IsoData IKONOS image

Table 3: Color interpretation for aerial photograph and images of IsoData classification						
Class	**Color**	**1936**	**1977**	**1999**	**CASI**	**IKONOS**
1	Red	Deep water	Deep water	Deep water	What is not part of the image	Mask
2	Green	Deep water and mangroves	Deep water, sea grass and mangroves	Deep water	Deep water and corals	Mangroves
3	Blue	Shallow water and mangroves	Shallow water, mangroves and sea grass	Shallow water, sea grass and mangroves	Deep water, coral, sea grass and mangroves	Deep water and mangroves
4	Yellow	Shallow water, submerged areas in coastal line and sea grass	Shallow water, sediment and sea grass	Shallow water, mangroves and sea grass	Shallow water, mangroves, coral and sea grass	Deep water, sea grass, and mangroves
5	Cyan	Submerged areas in coastal line land, sea grass and shallow water	Sea grass and shallow water	shallow water sea, grass and mangroves	Shallow water, sea grass, coral and mangroves	Shallow water and sea grass
6	Magenta	Submerged areas in coastal line, shallow water and sea grass	Shallow water, mangroves, coral and sea grass	Shallow water, mangroves. Coral and sea grass	Shallow water, sea grass and mangroves	Shallow water, coral and sea grass
7	Maroon	Sand, coral, urban areas, submerged and little vegetation areas in main land	Sand, coral, urban areas and areas with little or without vegetation	Sand, coral, urban areas and areas with little or no vegetation	Sand and urban areas	Sand, urban areas, coral areas little or no vegetation

K-Means classification shows a pattern similar to the one found in the urban areas, in the areas covered with sand and corals of the IsoData classification. It confuses the urban areas, the sandy regions and the corals and gives them the same class (class 5, blue). It is not a good method to determine increments in the urban areas. This must be, due to the quality (spatial resolution) of the photos and images, because if all the photos and images had a high spatial resolution the classification must had an outcome such as the one for the IKONOS image. In this image the urban areas are well seen and distinguished.

Sand and corals are not differentiated and since they are next to the other is difficult to determine which of them had changed their distribution through the years. There has been a decrease in their distribution as the years have passed, but which of them had been reduced is not determined with this method.

Mangroves were not well classified in the 1936 due to the same reason for which the IsoData method did not classify it well. It is for the limitation of the black and white photos. Only in the 1977 photo and the IKONOS image provide a clear distribution of the mangroves represented by the class 2 (green), but if it has increased or decreased through the year can not be determined, because of the lack of well classified photos or images of other years.

Sea grass are represented by the classes 4 (yellow) and 3 (blue) and its distribution change can be determined because it does not get confused with any other mentioned above. The only problem notable is the confusion presented in the CASI image where the sea grass blends with shallow water represented by the class 1. According with this classification the sea grass distribution has been increasing through the years. This method is adequate to determine changes through years in the distribution of the sea grass of La Parguera reefs.

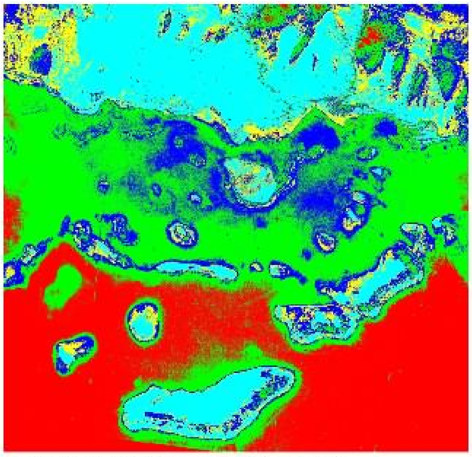

Figure 33: K-Means of the aerial photograph of 1936

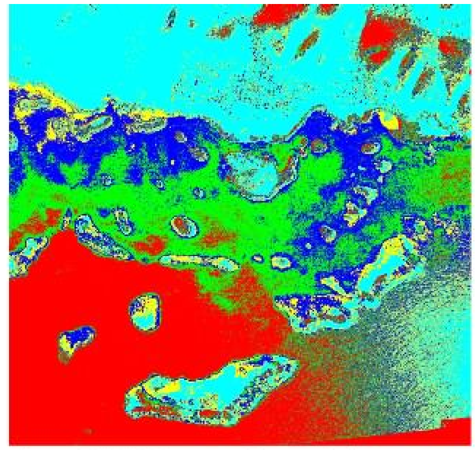

Figure 34: K-Means of the aerial photograph of 1977

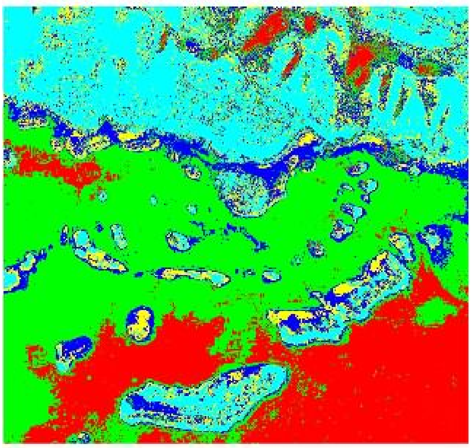

Figure 35: K-Means of the aerial photograph of 1999

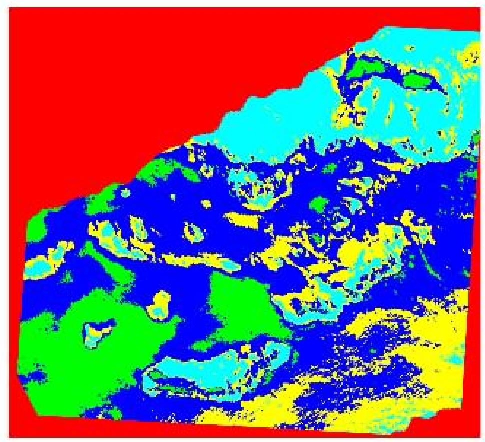

Figure 36: K-Means CASI image

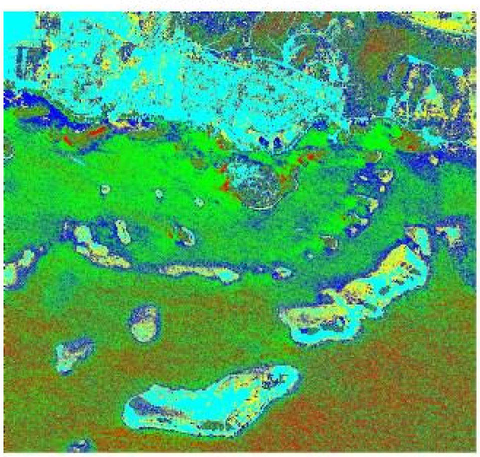

Figure 37: K-Means IKONOS image

Table 4: Color interpretation for aerial photograph and images of K-Means classification						
Class	**Color**	**1936**	**1977**	**1999**	**CASI**	**IKONOS**
1	Red	Deep water	Deep water, mangroves and sea grass	Deep water	What is not part of the photo	Mangroves and mask
2	Green	Shallow water, sea grass and mangroves	Shallow water, sea grass and mangroves	Shallow water	Deep water, sea grass, coral reefs and mangroves	Mangroves
3	Blue	Shallow water, sea grass, mangroves and submerged coastal line	Shallow water, sea grass and mangroves	Shallow water, sea grass and mangroves	Shallow water, sea grass, coral reefs and mangroves	Deep water, sea grass and mangroves
4	Yellow	Submerged coastal line and shallow water	Shallow water, coral reefs sea grass and mangroves	Shallow water, coral reefs sea grass and mangroves	Shallow water, coral reefs, sea grass and mangroves	Shallow water, sea grass coral reefs and mangroves
5	Cyan	Urban areas, sand, coral reefs, sea grass and submerged coastal line	Urban areas, coral reefs and sand	Urban areas, coral reefs and sand	Urban areas, coral reefs and sand	Urban areas, shallow water, coral reefs, areas with little or no vegetation and sand

Conclusion

Changes in time in the distribution or spectral response of the ecosystems of La Paraguera coral reefs can be dectected using Remote Sensing. These changes are detected using the Minimum Distance unsupervised classification. From the three classification used, this one detected more changes in distribution of the coral reefs of La Parguera. It detected urban areas increment, expansion in the sea grass communities and mangroves, and sand reduction. Though corals were distinguished, for this supervised method is difficult to detect changes through time in their distribution. The IsoData and K-Means only detected expansion in the sea grass communities. Therefore, none of these unsupervised methods are similar to the Minimum Distance method.

The best sensor for this work was the IKONOS because of its high spatial resolution. This make easier to differentiate from one class to the other. Camera sensor can also be used, but details are lost due to its low spatial resolution. Black and white photos are not the best option for this kind of work because of their limitation of color that confuses and loses information. CASI is not the best sensor from them all, because frequently, due to its low spatial resolution, details of the area were hard to see.

Although, processing the images with the classifications already mentioned, can detect changes through time in the distribution in La Pargueras coral reefs, the truth is that these changes are easily detected without the processing. Thus, classifying the images can help to determine the changes, but these changes can be detected comparing the original aerial photographs and images.

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Appendix

Appendix 1: Pixel description for the IsoData unsupervised classification

Pixel #	Pixel location	Coordinates	Aerial photograph						Images			
			1936		1977		1999		CASI		IKONOS	
			class	color	class	color	class	color	class	color	class	color
1	1588, 4719	17°57’36.43‶ N, 67°02’52.46” W	2	green	1	red	2	green	3	blue	4	yellow
2	619, 4180	17°57’53.85‶ N, 67°03’25.45” W	1	red	1	red	2	green	3	blue	4	yellow
3	1658, 4643	17°57’38.91‶ N, 67°02’50.09” W	2	green	1	red	2	green	3	blue	4	yellow
4	905,4540	17°57’42.18‶ N, 67°03’15.69” W	2	green	1	red	2	green	3	blue	4	yellow
5	2066, 4337	17°57’48.91‶ N, 67°02’36.25” W	2	green	3	green	2	green	5	cyan	5	cyan
6	1744, 3941	17°58’1.75”N, 67°02’47.24” W	3	blue	2	green	3	blue	5	cyan	3	blue
7	623, 4358	17°57’48.06‶N, 67°03’25.29‶ W	3	blue	1	red	3	blue	4	yellow	3	blue
8	2513, 3403	17°58’19.33‶ N, 67°02’21.17” W	4	yellow	5	cyan	4	yellow	5	cyan	5	cyan
9	2182, 4393	17°57’47.10‶ N, 67°02’32.31” W	3	blue	2	green	2	green	5	cyan	4	yellow
10	548, 4097	17°57’56.55‶ N, 67°03’27.87” W	3	blue	1	red	2	green	4	yellow	5	Cyan
11	1749, 5182	17°57’21.39‶ N, 67°02’46.93‶ W	7	maroon	7	maroon	6	magenta	7	maroon	7	maroon
12	2027, 5032	17°57’26.30‶ N, 67°02’ 37.50” W	5	cyan	4	yellow	5	cyan	4	yellow	6	magenta
13	2436, 4581	17°57’41.01‶ N, 67°02’23.65” W	7	maroon	4	yellow	5	cyan	6	magenta	7	maroon
14	2869, 4309	17°57’49.90‶ N, 67°2’8.97” W	7	maroon	7	maroon	4	yellow	7	maroon	6	magenta
15	2081, 5018	17°57’26.75‶ N, 67°02’37.81” W	7	maroon	5	cyan	5	cyan	4	yellow	5	cyan
16	2438, 4746	17°57’39.82‶ N, 67°02’29.29 W	4	yellow	6	magenta	5	cyan	5	cyan	5	cyan
17	1268, 5325	17°57’23.42‶ N, 67°03’3.15” W	7	maroon	7	maroon	7	maroon	7	maroon	7	maroon
18	1828, 5092	17°57’24.32‶ N, 67°02’44.26”W	7	maroon	7	maroon	5	cyan	5	cyan	6	magenta
19	2796, 4423	17°57’46.19‶ N, 67°02’44.26” W	7	maroon	7	maroon	4	yellow	6	magenta	5	cyan
20	3000, 4266	17°57’51.32‶ N, 67°02’4.52”W	7	maroon	7	maroon	4	yellow	7	maroon	6	magenta

Appendix 1: Pixel description for the IsoData classification continuation												
Pixel #	Pixel location	Coordinates	Aerial photograph						Images			
			1936		1977		1999		CASI		IKONOS	
			class	color	class	color	class	color	class	color	class	color
21	3075, 3360	17°58’20.79` N, 67°02’2.07” W	3	blue	2	green	3	blue	4	yellow	2	green
22	2961, 3382	17°58’20.03` N, 67°02’5.94” W	3	blue	1	red	4	yellow	4	yellow	3	blue
23	1983, 3417	17°58’18.79` N, 67°02’29.15” W	5	cyan	7	maroon	7	maroon	7	maroon	7	maroon
24	2463, 4073	17°57’57.54` N, 67° 02’22.79” W	4	yellow	1	red	1	red	2	green	4	yellow
25	2718, 3781	17°58’7.06` N, 67°02’14.16” W	4	yellow	4	yellow	6	magenta	4	yellow	2	green
26	1261, 5346	17°57’16.00` N, 67°03’3.50” W	5	cyan	2	green	4	yellow	3	blue	5	cyan
27	1918, 5265	17°57’18.71` N, 67°02’4118” W	4	yellow	3	blue	7	maroon	5	cyan	7	maroon
28	1879, 5240	17°57’19.51` N, 67°02’42.51” W	7	maroon	2	green	7	maroon	5	cyan	7	maroon
29	2493, 4724	17°57’36.36` N, 67°02’21.70” W	3	blue	7	maroon	7	maroon	7	maroon	7	maroon
30	2964, 4386	17°57’47.41` N, 67°02’5.73” W	4	yellow	5	cyan	6	magenta	5	cyan	7	magenta
31	2960, 3260	17°58’24.03` N, 67°02’5.99” W	3	blue	7	maroon	4	yellow	7	maroon	7	maroon
32	1952, 3179	17°58’26.56` N, 67°02’40.26”W	7	maroon	7	maroon	7	maroon	7	maroon	7	maroon
33	1565, 3219	17°58’25.22` N, 67°02’53.41” W	7	maroon	7	maroon	7	maroon	7	maroon	7	maroon
34	1983, 3579	17°58’13.55` N, 67°02’36.16” W	2	green	7	maroon	7	maroon	7	maroon	7	maroon
35	1594, 3297	17°58’22.68` N, 67°02’52.41” W	3	blue	7	maroon	7	maroon	7	maroon	7	maroon
36	1970, 3415	17°58’18.88` N, 67°02’39.62” W	5	cyan	7	maroon	7	maroon	7	maroon	7	maroon
37	2965, 3380	17°58’20.13` N, 67°02’5.81” W	3	blue	1	red	3	blue	4	yellow	3	blue
38	1625, 3269	17°58’23.60` N, 67°02’51.36” W	6	magenta	7	maroon	7	maroon	7	maroon	7	maroon
39	2611, 3280	17°58’23.34` N, 67°02’17.85” W	6	magenta	7	maroon	7	maroon	7	maroon	7	maroon
40	1622, 3236	17°58’24.67` N, 67°02’51.47” W	6	magenta	7	maroon	7	maroon	7	maroon	7	maroon

Appendix 2: Pixel description for the K-Means unsupervised classification												
Pix el #	Pixel locatio n	Coordinates	Aerial photograph						Images			
			1936		1977		1999		CASI		IKONOS	
			class	color	class	color	class	color	class	color	class	color
1	1588, 4719	17°57'36.43` N, 67°02'52.46" W	1	red	1	red	1	red	3	blue	3	blue
2	619, 4180	17°57'53.85` N, 67°03'25.45" W	1	red	1	red	2	green	3	blue	3	blue
3	1658, 4643	17°57'38.91` N, 67°02'50.09" W	1	red	1	red	1	red	2	green	3	blue
4	905,45 40	17°57'42.18` N, 67°03'15.69" W	1	red	1	red	2	green	2	green	3	blue
5	2066, 4337	17°57'48.91` N, 67°02'36.25" W	2	green	2	green	2	green	3	blue	4	yellow
6	1744, 3941	17°58'1.75"N, 67°02'47.24" W	3	blue	2	green	2	green	3	blue	4	yellow
7	623, 4358	17°57'48.06`"N, 67°03'25.29` W	2	green	1	red	2	green	3	blue	4	yellow
8	2513, 3403	17°58'19.33` N, 67°02'21.17" W	3	blue	3	blue	3	blue	3	blue	4	yellow
9	2182, 4393	17°57'47.10` N, 67°02'32.31" W	2	green	2	green	2	green	3	blue	4	yellow
10	548, 4097	17°57'56.55` N, 67°03'27.87" W	2	green	1	red	2	green	3	blue	4	yellow
11	1749, 5182	17°57'21.39` N, 67°02'46.93` W	5	cyan	5	cyan	4	yellow	5	cyan	5	cyan
12	2027, 5032	17°57'26.30` N, 67°02' 37.50" W	4	yellow	3	blue	4	yellow	3	blue	4	tellow
13	2436, 4581	17°57'41.01` N, 67°02'23.65" W	5	cyan	3	blue	4	yellow	5	cyan	5	cyan
14	2869, 4309	17°57'49.90` N, 67°2'8.97" W	5	cyan	5	cyan	3	blue	5	cyan	4	yellow
15	2081, 5018	17°57'26.75` N, 67°02'37.81" W	2	green	2	green	4	yellow	5	cyan	4	yellow
16	2438, 4746	17°57'39.82` N, 67°02'29.29 W	5	cyan	3	blue	5	cyan	5	cyan	5	cyan
17	1268, 5325	17°57'23.42` N, 67°03'3.15" W	3	blue	3	blue	3	blue	2	green	3	blue
18	1828, 5092	17°57'24.32` N, 67°02'44.26"W	5	cyan	5	cyan	3	blue	3	blue	4	yellow
19	2796, 4423	17°57'46.19` N, 67°02'44.26" W	5	cyan	5	cyan	3	blue	4	yellow	4	yellow
20	3000, 4266	17°57'51.32` N, 67°02'4.52"W	5	cyan	5	cyan	3	blue	5	cyan	4	yellow

Appendix 2: Pixel description for the K-Means classification continuation

Pixel #	Pixel location	Coordinates	Aerial photograph						Images			
			1936		1977		1999		CASI		IKONOS	
			class	color	class	color	class	color	class	color	class	color
21	3075, 3360	17˚58’20.79` N, 67˚02’2.07” W	2	green	2	green	3	blue	3	blue	2	green
22	2961, 3382	17˚58’20.03` N, 67˚02’5.94” W	3	blue	4	yellow	3	blue	4	yellow	3	blue
23	1983, 3417	17˚58’18.79` N, 67˚02’29.15” W	4	yellow	5	cyan	5	cyan	5	cyan	5	cyan
24	2463, 4073	17˚57’57.54` N, 67˚ 02’22.79” W	4	yellow	5	cyan	5	cyan	5	cyan	5	cyan
25	2718, 3781	17˚58’7.06` N, 67˚02’14.16” W	3	blue	3	blue	4	yellow	3	blue	2	green
26	1261, 5346	17˚57’16.00` N, 67˚03’3.50” W	4	yellow	5	cyan	5	cyan	5	cyan	5	cyan
27	1918, 5265	17˚57’18.71` N, 67˚02’4118” W	3	blue	2	green	5	cyan	4	yellow	5	cyan
28	1879, 5240	17˚57’19.51` N, 67˚02’42.51” W	1	red	1	red	1	red	2	green	3	blue
29	2493, 4724	17˚57’36.36` N, 67˚02’21.70” W	3	blue	5	cyan	5	cyan	5	cyan	5	cyan
30	2964, 4386	17˚57’47.41` N, 67˚02’5.73” W	3	blue	4	yellow	5	cyan	3	blue	5	cyan
31	2960, 3260	17˚58’24.03` N, 67˚02’5.99” W	3	blue	5	cyan	3	blue	5	cyan	5	cyan
32	1952, 3179	17˚58’26.56` N, 67˚02’40.26”W	5	cyan	5	cyan	5	cyan	5	cyan	5	cyan
33	1565, 3219	17˚58’25.22` N, 67˚02’53.41” W	5	cyan	5	cyan	5	cyan	5	cyan	5	cyan
34	1983, 3579	17˚58’13.55` N, 67˚02’36.16” W	3	blue	4	yellow	5	cyan	5	cyan	5	cyan
35	1594, 3297	17˚58’22.68` N, 67˚02’52.41” W	2	green	5	cyan	5	cyan	5	cyan	5	cyan
36	1970, 3415	17˚58’18.88` N, 67˚02’39.62” W	3	blue	5	cyan	5	cyan	5	cyan	5	cyan
37	2965, 3380	17˚58’20.13` N, 67˚02’5.81” W	3	blue	1	red	3	blue	3	blue	2	green
38	1625, 3269	17˚58’23.60` N, 67˚02’51.36” W	4	yellow	5	cyan	5	cyan	5	cyan	5	cyan
39	2611, 3280	17˚58’23.34` N, 67˚02’17.85” W	4	yellow	5	cyan	5	cyan	5	cyan	5	cyan
40	1622, 3236	17˚58’24.67` N, 67˚02’51.47” W	4	yellow	5	cyan	5	cyan	5	cyan	5	cyan

Appendix 3: Pixel description for the Minimum Distance supervised classification

Pixel #	Pixel location	Coordinates	Aerial photograph						Images			
			1936		1977		1999		CASI		IKONOS	
			class	color	class	color	class	color	class	color	class	color
1	1588, 4719	17°57’36.43` N, 67°02’52.46” W	DW	red	DW	red	DW	red	SW	thistle 2	DW	red
2	619, 4180	17°57’53.85` N, 67°03’25.45” W	DW	red	DW	red	SW	thistle 2	DW	red	DW	red
3	1658, 4643	17°57’38.91` N, 67°02’50.09” W	DW	red	DW	red	DW	red	DW	red	DW	red
4	905,4540	17°57’42.18` N, 67°03’15.69” W	DW	red	DW	red	DW	red	DW	red	DW	red
5	2066, 4337	17°57’48.91` N, 67°02’36.25” W	M	green	SW	thistle 2	SW	thistle 2	SW	thistle 2	SW	thistle 2
6	1744, 3941	17°58’1.75”N, 67°02’47.24” W	SW	thistle 2	SW	thistle 2	SW	thistle 2	SW	thistle 2	SW	thistle 2
7	623, 4358	17°57’48.06”N, 67°03’25.29` W	SW	thistle 2	DW	red	SW	thistle 2	SW	thistle 2	SW	thistle 2
8	2513, 3403	17°58’19.33` N, 67°02’21.17” W	SG	Yellow 3	C	coral	M	green	SG	Yellow 3	SW	thistle 2
9	2182, 4393	17°57’47.10` N, 67°02’32.31” W	M	green	SW	thistle 2	DW	red	SW	thistle 2	SW	thistle 2
10	548, 4097	17°57’56.55` N, 67°03’27.87” W	SW	thistle 2	DW	red	SW	thistle 2	SW	thistle 2	SW	thistle 2
11	1749, 5182	17°57’21.39` N, 67°02’46.93` W	S	yellow	S	yellow	C	coral	S	yellow	S	yellow
12	2027, 5032	17°57’26.30` N, 67°02’ 37.50” W	C	coral	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3
13	2436, 4581	17°57’41.01` N, 67°02’23.65” W	C	coral	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3
14	2869, 4309	17°57’49.90` N, 67°2’8.97” W	C	coral	S	Yellow	SG	Yellow 3	C	coral	SG	Yellow 3
15	2081, 5018	17°57’26.75` N, 67°02’37.81” W	SW	thistle 3	SW	thistle 3	SG	Yellow 3	C	coral	SG	Yellow 3
16	2438, 4746	17°57’39.82` N, 67°02’29.29 W	C	coral	C	coral	C	coral	C	coral	S	sand
17	1268, 5325	17°57’23.42` N, 67°03’3.15” W	SG	Yellow 3	SG	Yellow 3	M	green	M	green	C	coral
18	1828, 5092	17°57’24.32` N, 67°02’44.26”W	S	yellow	S	yellow	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3
19	2796, 4423	17°57’46.19` N, 67°02’44.26” W	S	yellow	S	yellow	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3
20	3000, 4266	17°57’51.32` N, 67°02’4.52”W	S	yellow	S	yellow	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3

DW= deep water, SW= shallow water, S= sand, M= mangroves, C= corals, SG= sea grass, UA= urban areas

Appendix 1: Pixel description for the Minimum Distance supervised classification continuation												
Pixel #	**Pixel location**	**Coordinates**	**Aerial photograph**						**Images**			
			1936		**1977**		**1999**		**CASI**		**IKONOS**	
			class	**color**	**class**	**color**	**class**	**color**	**class**	**color**	**class**	**color**
21	3075, 3360	17°58’20.79″ N, 67°02’2.07” W	SW	thistle 2	SW	thistle 2	M	green	M	green	M	green
22	2961, 3382	17°58’20.03″ N, 67°02’5.94” W	SW	thistle 2	DW	red	M	green	M	green	M	green
23	1983, 3417	17°58’18.79″ N, 67°02’29.15” W	C	corals	S	yellow	U A	Orange 1	U A	Orange 1	U A	Orange 1
24	2463, 4073	17°57’57.54″ N, 67° 02’22.79” W	SG	Yellow 3	DW	red	DW	red	DW	red	M	green
25	2718, 3781	17°58’7.06″ N, 67°02’14.16” W	SG	Yellow 3	SG	Yellow 3	SG	Yellow 3	M	green	M	green
26	1261, 5346	17°57’16.00″ N, 67°03’3.50” W	C	coral	C	coral	C	coral	C	coral	C	coral
27	1918, 5265	17°57’18.71″ N, 67°02’4118” W	SG	Yellow 3	SW	Thistle 3	C	coral	SG	Yellow 3	S	yellow
28	1879, 5240	17°57’19.51″ N, 67°02’42.51” W	S	yellow	SW	thistle 3	C	coral	SG	thistle 3	S	yellow
29	2493, 4724	17°57’36.36″ N, 67°02’21.70” W	C	coral	S	yellow	UA	Orange 1	C	coral	S	yellow
30	2964, 4386	17°57’47.41″ N, 67°02’5.73” W	C	coral	C	coral	C	coral	SG	thistle 2	C	coral
31	2960, 3260	17°58’24.03″ N, 67°02’5.99” W	SW	thistle	UA	Orange 1	M	green	C	coral	M	green
32	1952, 3179	17°58’26.56″ N, 67°02’40.26”W	C	coral	UA	Orange 1	UA	Orange 1	UA	Orange 1	UA	Orange 1
33	1565, 3219	17°58’25.22″ N, 67°02’53.41” W	C	coral	UA	Orange 1	UA	Orange 1	UA	Orange 1	UA	Orange 1
34	1983, 3579	17°58’13.55″ N, 67°02’36.16” W	M	green	UA	Orange 1	UA	Orange 1	UA	Orange 1	UA	Orange 1
35	1594, 3297	17°58’22.68″ N, 67°02’52.41” W	C	coral	UA	Orange 1	UA	Orange 1	UA	Orange 1	UA	Orange 1
36	1970, 3415	17°58’18.88″ N, 67°02’39.62” W	C	coral	UA	Orange 1	UA	Orange 1	C	coral	C	coral
37	2965, 3380	17°58’20.13″ N, 67°02’5.81” W	SW	thistle 2	DW	red	M	green	M	green	M	green
38	1625, 3269	17°58’23.60″ N, 67°02’51.36” W	C	coral	UA	Orange 1	UA	Orange 1	C	coral	UA	Orange 1
39	2611, 3280	17°58’23.34″ N, 67°02’17.85” W	C	coral	UA	Orange 1	C	coral	UA	Orange 1	C	coral
40	1622, 3236	17°58’24.67″ N, 67°02’51.47” W	C	coral	UA	Orange 1	UA	Orange 1	UA	Orange 1	UA	Orange 1

DW= deep water, SW= shallow water, S= sand, M= mangroves, C= corals, SG= sea grass, UA= urban areas