University of Puerto Rico
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Undergraduate Research Final Report:

Development of a site-specific algorithm to estimate suspended sediments using MODIS

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Abstract:

Studies of large and dynamic areas are facilitated nowadays by the use of remote sensing systems. In a previous project, MODIS Band 1 was used to validate an algorithm developed by Miller and McKee in 2004 to study the coastal waters of the Northern Gulf of Mexico. However, the suggested formula was proven to be inconsistent when it was applied to examine the relationships between suspended sediment concentration and remotely sensed reflectance of Mayagüez Bay, Puerto Rico. The present study sought to develop a site-specific algorithm, but low correlation values were found on various scenarios. These values were $R^2 = 0.1443$ (general), $R^2 = 0.0695$ (dry seasons), $R^2 = 0.2788$ (rainy seasons), $R^2 = 0.0473$ (in-shore sites), and $R^2 = 0.0468$ (out-shore sites). Nevertheless, certain information on suspended sediment dynamics may be studied based on this sensor's spatial and spectral resolutions.

Keywords: MODIS, Band 1, suspended sediments, Mayagüez Bay

Introduction:

Advances in remote sensing techniques now allow the study of large and dynamic areas with little extensive fieldwork. However, it has become increasingly important to develop better algorithms for the accurate estimation of diverse parameters, such as suspended sediments. These materials are responsible for changing the optical properties of water in coastal areas (Lugo, 2002). Furthermore, sediments are a major problem in streams, lakes, and estuaries and carry adsorbed chemicals, affecting aquatic ecosystems (Ritchie *et al.*, 1976).

Many studies have suggested algorithms for the relationship between the concentration of suspended sediments and the amount of light leaving the water surface: known as water-leaving radiance (or reflectance if calibrated against the incoming sunlight). Suspended sediments increase the water-leaving radiance in the visible and near infrared proportion of the electromagnetic spectrum (Figure 1). Most research working with high suspended sediment concentrations have found a curvilinear relationship between suspended sediments and radiance or reflectance because the amount of reflected radiance tends to saturate as suspended sediment concentrations increase (Ritchie and Cooper, 2001).

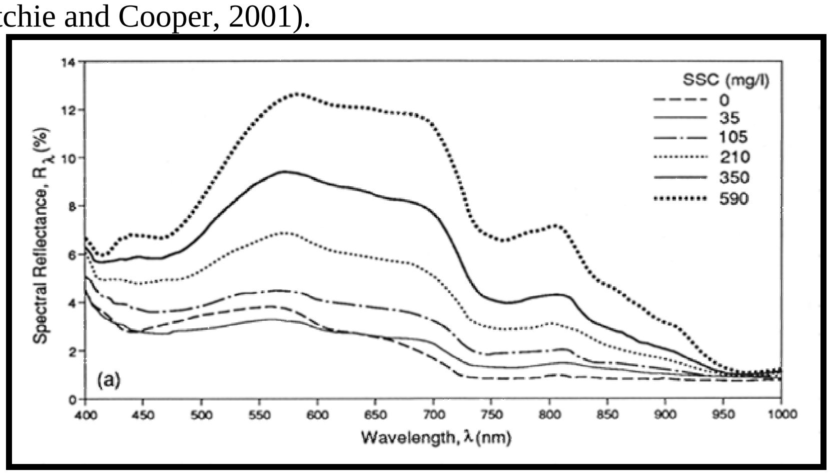


Figure 1: Reflectance as a function of wavelength for varying suspended sediment concentrations
(from Chen *et al.*, 1992)

Mayagüez Bay (between latitude 18° 10' N and 18° 16' N and longitude 67° 10' W and 67° 14' W), shown in Figure 2, is influenced by the discharge of three river systems: Añasco, Yagüez, and Guanajibo. This area is also affected by anthropogenic activities (Rivera, 2003). The sediments deposited on the shore produce changes in ocean color (González, 2005). In turn, there is an impact on organisms such as phytoplankton biomass (Gilbes et al., 1996) and growth rate of coral reef (Cuevas, 2004). These factors are enhanced by seasonal river discharge and land run-off (Gilbes et al., 2002).

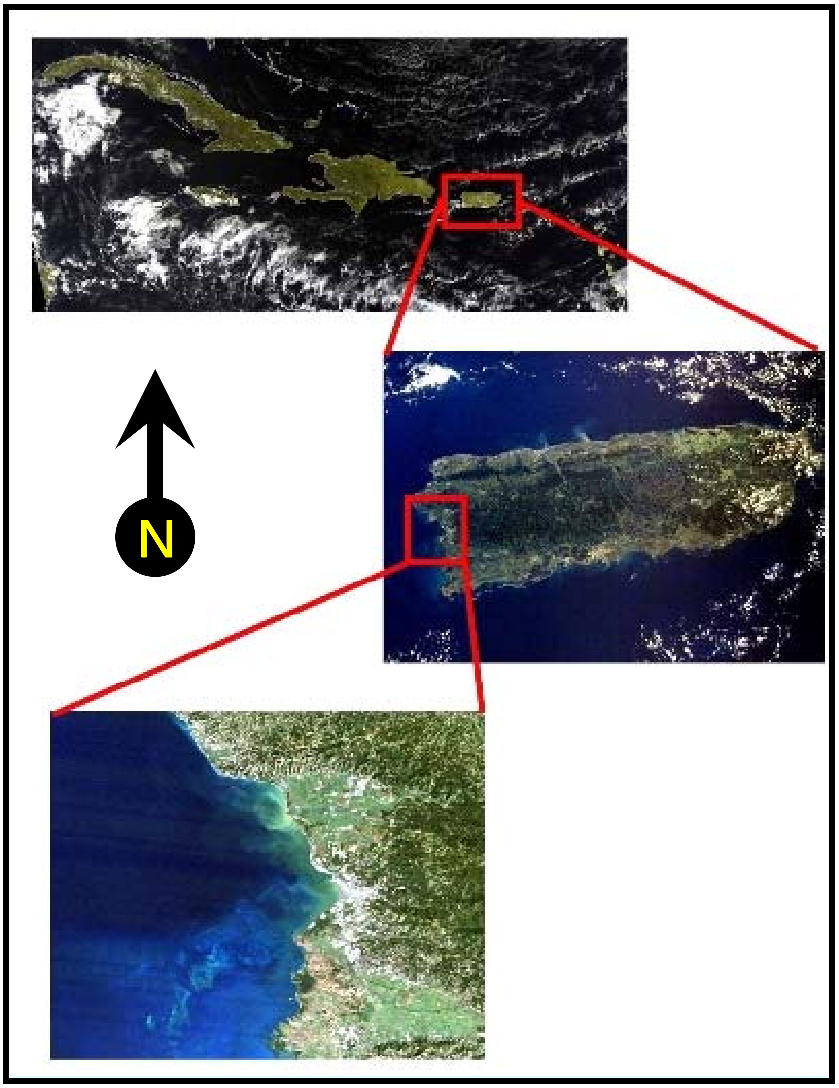


Figure 2: Location of study area: Mayagüez Bay, Puerto Rico
(images provided by the GERS Laboratory)

In the previous part of this undergraduate research, an algorithm was tested in Mayagüez Bay using Band 1 of MODIS (Moderate Resolution Imaging Spectroradiometer) images. The algorithm was developed by Miller and McKee in 2004. The equation was:

$$1140.25*(\text{MODIS Band 1}) - 1.91$$

Their research with MODIS Band 1 provided results of total suspended matter (TSM) in the coastal waters off the northern Gulf of Mexico. They stated that this approach is reasonably robust in coastal and inland waters because scattering from suspended materials frequently dominates the reflectance spectra when compared to pure water and phytoplankton absorption (Miller and McKee, 2004).

Figure 3 shows their linear relationship established between MODIS Terra 250 m Band 1 data (620 – 670 nm) and *in situ* measurements of TSM, providing evidence of the transport and fate of materials in coastal environments (Miller and McKee, 2004).

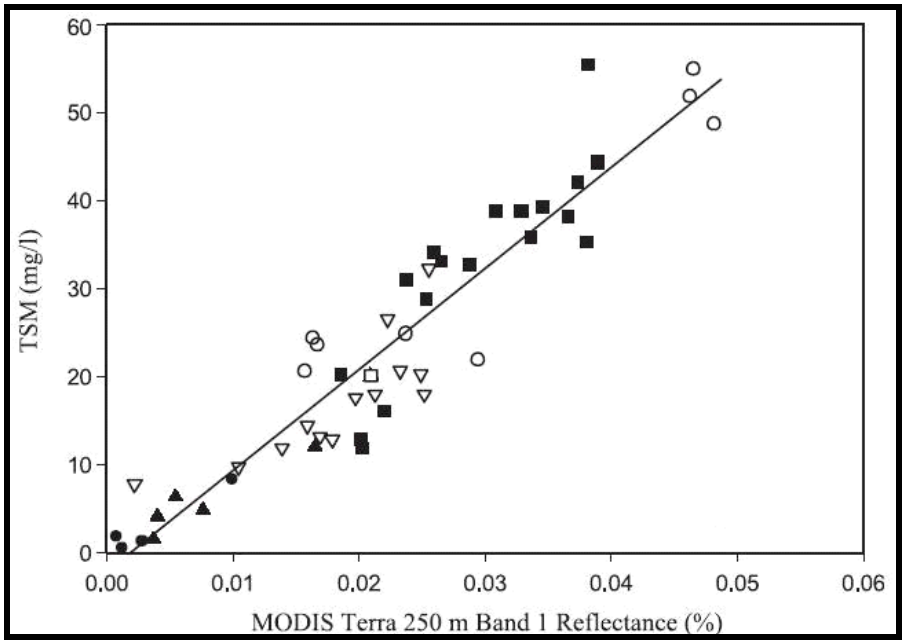


Figure 3: Total suspended matter as a function of atmospherically corrected MODIS Terra 250 m Band 1 reflectance as obtained by Miller and McKee (2004).

The raw digital values of each available image of Mayagüez Bay were converted to suspended sediment concentrations using the Miller and McKee (2004) algorithm.

After a careful processing and analysis, the project provided results that were several times higher than those measured in the field. The correlation value obtained from the resulting linear relationship was very low and unreliable (R^2 = 0.0845). This proved that the algorithm developed by Miller and McKee (2004) was inconsistent throughout Mayagüez Bay (Figure 4), having atmospheric effects and differences in discharge (Mayagüez Bay versus Northern Gulf of Mexico) as possible reasons. It was concluded that a site-specific algorithm was needed to better study the area (Martínez, 2007).

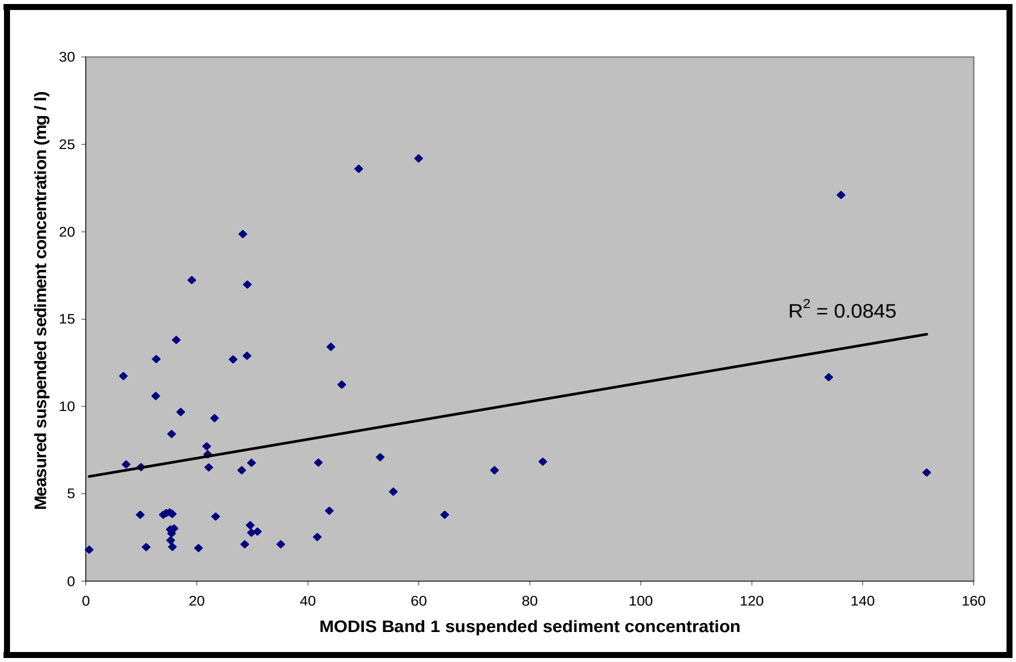


Figure 4: Relationship of suspended sediment concentrations as measured in the field and with MODIS Terra 250 m Band 1 determined by Martínez (2007).

The purpose of the current study was to develop such an algorithm to better understand the dynamics of suspended sediments at Mayagüez Bay, which can be analyzed based on temporal variability (i.e. rainy versus dry seasons), distribution of concentrations along plumes, optical properties, and water quality. It is expected that this project will give a better relationship between the field data and MODIS Band 1 values, and thus become a foothold for new researches to various other questions and applications.

Methodology:

The first phase of this project was data collection. The field data was already available as the measurements were taken during several field campaigns from 2001 through 2006. Only 13 out of a total of 24 sites had suspended sediments concentration measurements. Also, each one had specific geographical coordinates based on GPS (Table 1 and Figure 5). The other data was the spectral images from the MODIS sensor. This is a major instrument on the Earth Observing System (EOS)-AM1 and EOS-PM1 missions, Terra and Aqua, respectively. MODIS has the capability to observe nearly the entire earth every two days via a set of 36 spectral bands at nadir geometric instantaneous-fields-of-view (GIFOV's) of 250, 500, and 1000 m and provide key observations of the atmosphere, oceans, and land surfaces (Barnes et al., 1998). As it was stated before, the focus was set on MODIS Terra Band 1 (250 m spatial resolution and a spectral range of 620-670 nm). A total of 34 MODIS images were downloaded from NASA Archive Center, at Level 1b (raw data)-Collection 5. These images correspond to the dates in which field measurements were taken. In addition, 17 GPS coordinates were taken as reference.

Table 1: Locations of sampling stations

STATION	LATITUDE	LONGITUDE	STATION	LATITUDE	LONGITUDE
*1, A1**	18^{o} 16.00'	67^{o} 12.00'	*13, Y1**	18^{o} 12.20'	67^{o} 09.78'
2	18^{o} 16.00'	67^{o} 13.10'	*14*	18^{o} 12.20'	67^{o} 10.85'
3	18^{o} 16.00'	67^{o} 14.10'	*15*	18^{o} 12.20'	67^{o} 11.95'
*4, A2**	18^{o} 16.00'	67^{o} 15.20'	*16, Y2**	18^{o} 12.20'	67^{o} 12.95'
*5, AAA**	18^{o} 14.40'	67^{o} 11.40'	*17*	18^{o} 11.33'	67^{o} 10.80'
6	18^{o} 14.40'	67^{o} 12.40'	*18*	18^{o} 11.33'	67^{o} 11.85'
7	18^{o} 14.40'	67^{o} 13.50'	*19*	18^{o} 11.33'	67^{o} 12.90'
*8, AAA2**	18^{o} 14.40'	67^{o} 14.50'	*20*	18^{o} 11.33'	67^{o} 14.05'
9	18^{o} 13.14'	67^{o} 10.14'	*21, G1**	18^{o} 10.25'	67^{o} 11.10'
10	18^{o} 13.14'	67^{o} 11.18'	*22*	18^{o} 10.25'	67^{o} 12.10'
11	18^{o} 13.14'	67^{o} 12.25'	*23*	18^{o} 10.25'	67^{o} 13.15'
12	18^{o} 13.14'	67^{o} 13.32'	*24, G2**	18^{o} 10.25'	67^{o} 14.80'

* = sampled since 2005

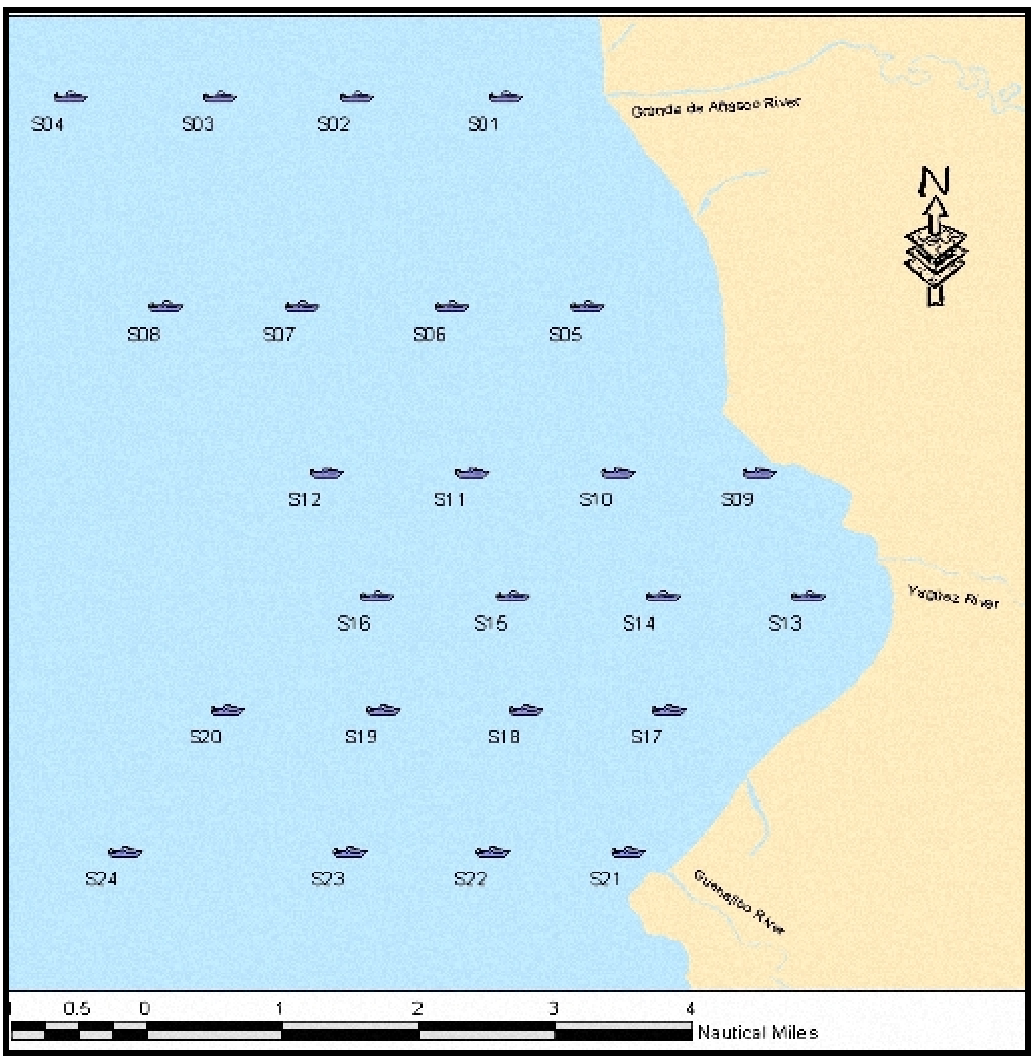


Figure 5: Location of sampling stations throughout Mayagüez Bay.

The second phase consisted in the images preprocessing. The software used was ENVI 4.3 (Environment for Visualization of Images). First, the images were geo-referenced to Puerto Rico's region. The selected system was UTM (Universal Transverse Mercator), designating the region 19 North and NAD83 (North America 1983) as datum. The 17 GPS points were corroborated in order to establish ground truth to the geo-referencing procedure. Next, the images were subjected to atmospheric correction using the Dark Subtract routine. With this technique the darkest pixel in each image (lowest reflectance value) using band 2 was selected to fix the standard procedure already implemented in the software. In addition, quality control parameters such as cloud coverage and data errors were taken into account.

The third phase of this methodology was data extraction. A shape-file was developed using ArcGIS and the coordinates of each station. The resulting vector layer was loaded into ENVI 4.3 and was exported as regions of interest (ROI). After overlaying these ROIs to each image, the reflectance values were extracted. Only the clearest images were considered to establish relationships between suspended sediment concentration and reflectance percent. This criterion was based on the least cloud coverage and data errors over Mayagüez Bay.

The last phase consisted in data correlation and analysis. The extracted reflectance data was empirically related to the *in situ* field measurements. A linear regression was established between these factors in order to determine its correlation value (R^2) and the possible equation of the new algorithm. Depending on the reliability of the results, the new equation may be applied to other products (i.e. remaining stations or other MODIS images), converting their raw digital values to suspended sediment concentration data, and study the dynamics of these materials later on.

Results:

Various results were encountered after completing the processing of the clearest images available during the 2001-2006 field data collection campaigns. However, the routines had basically the same distribution. It is true that the reflectance ranges of some images were kept within a realistic threshold, but still, these values turned out to have a large variability. Some low suspended sediment concentration measurements had different reflectance percentages. The relationship established was not accurate enough to establish a good linear regression, resulting in low correlation values. Various relationships are shown on Figures 6, 7, and 8, and the values per station in Table 2.

Table 2: Field data and reflectance values per date and station

Date	Stations	MODIS	Field
24-Apr-01	1	0.087743	16.07
25-Apr-01	7	0.042682	6.53
	9	0.075269	10.72
26-Apr-01	19	0.041044	2.12
	23	0.042135	3.20
2-Oct-01	1	0.098019	23.6
	4	0.0652	1.95

4-Oct-01	17	0.051672	12.9
	21	0.06014	6.35
	23	0.034269	3.8
27-Feb-02	11	0.04564	5.23
22-Aug-02	17	0.220356	10.8
	19	0.220384	6.22
	21	0.186196	22.1
	23	0.201269	11.67
25-Feb-03	1	0.065775	21.19
	4	0.022134	7.14
26-Feb-03	5	0.029578	13.81
	9	0.054052	13.41
	11	0.028998	6.68
	13	0.047365	12.71
	15	0.030777	11.74
27-Feb-03	17	0.03478	12.69
	19	0.029222	6.51
	21	0.041589	16.98
	23	0.033081	7.26
7-Oct-03	1	0.053717	18.93
	4	0.026242	7.03
	5	0.0284	12.85
	7	0.02525	6.77
8-Oct-03	9	0.088664	8.99
	11	0.037398	6.57
	13	0.056154	9.21
	15	0.039913	10.90
9-Oct-03	17	0.033815	11.75
	19	0.030291	6.33
	21	0.039911	50.54
	23	0.030411	5.74
12-Jan-04	1	0.067214	6.79
	7	0.062205	3.94
13-Jan-04	5	0.036517	7.72
	9	0.073402	6.84
	11	0.02616	3.85
	13	0.049228	9.33
	15	0.030416	8.42
14-Jan-04	17	0.036296	9.68

	19	0.019051	2.34
	21	0.046669	17.23
	23	0.017366	3.02
12-Feb-04	1	0.040444	15.11
	2	0.035284	2.41
	3	0.020517	5.57
	13	0.03291	3.84
	14	0.021656	3.33
	15	0.018397	3.09
	21	0.028028	4.73
	22	0.019085	2.70
	23	0.018099	4.20
10-Mar-05	A1	0.078872	3.80
	A2	0.033529	3.00
	AAA	0.038823	3.70
	Y1	0.073109	2.73
	G1	0.048228	3.33
	G2	0.035184	2.43
19-Jul-05	A2	0.072147	2.82
	G2	0.063919	1.85
17-Aug-05	A1	0.121091	24.15
	A2	0.03357	3.27
	AAA	0.094798	6.50
	G2	0.051666	13.37
20-Sep-05	A2	0.171795	1.60
	AAA	0.081343	2.63
	Y1	0.121666	6.93
	G1	0.081969	6.77
	G2	0.146209	1.73
19-Oct-05	A1	0.054027	5.13
	A2	0.025413	1.90
	AAA	0.034149	4.92
	Y1	0.340616	8.03
	G1	0.033658	19.87
	G2	0.021465	1.97
6-Dec-05	A2	0.080559	2.42
	AAA	0.023069	2.97
	Y1	0.045666	10.60
	G1	0.038838	6.65

	G2	0.020868	1.80
8-Mar-06	A1	0.073954	6.35
	A2	0.047919	2.53
	AAA	0.045424	4.03
	Y1	0.067877	7.10
	G1	0.072782	24.20
	G2	0.043862	2.12
26-Oct-06	A1	0.065612	7.95
	A2	0.04037	1.22
	AAA	0.035452	1.72
	Y1	0.054823	2.58
	G1	0.059765	2.42

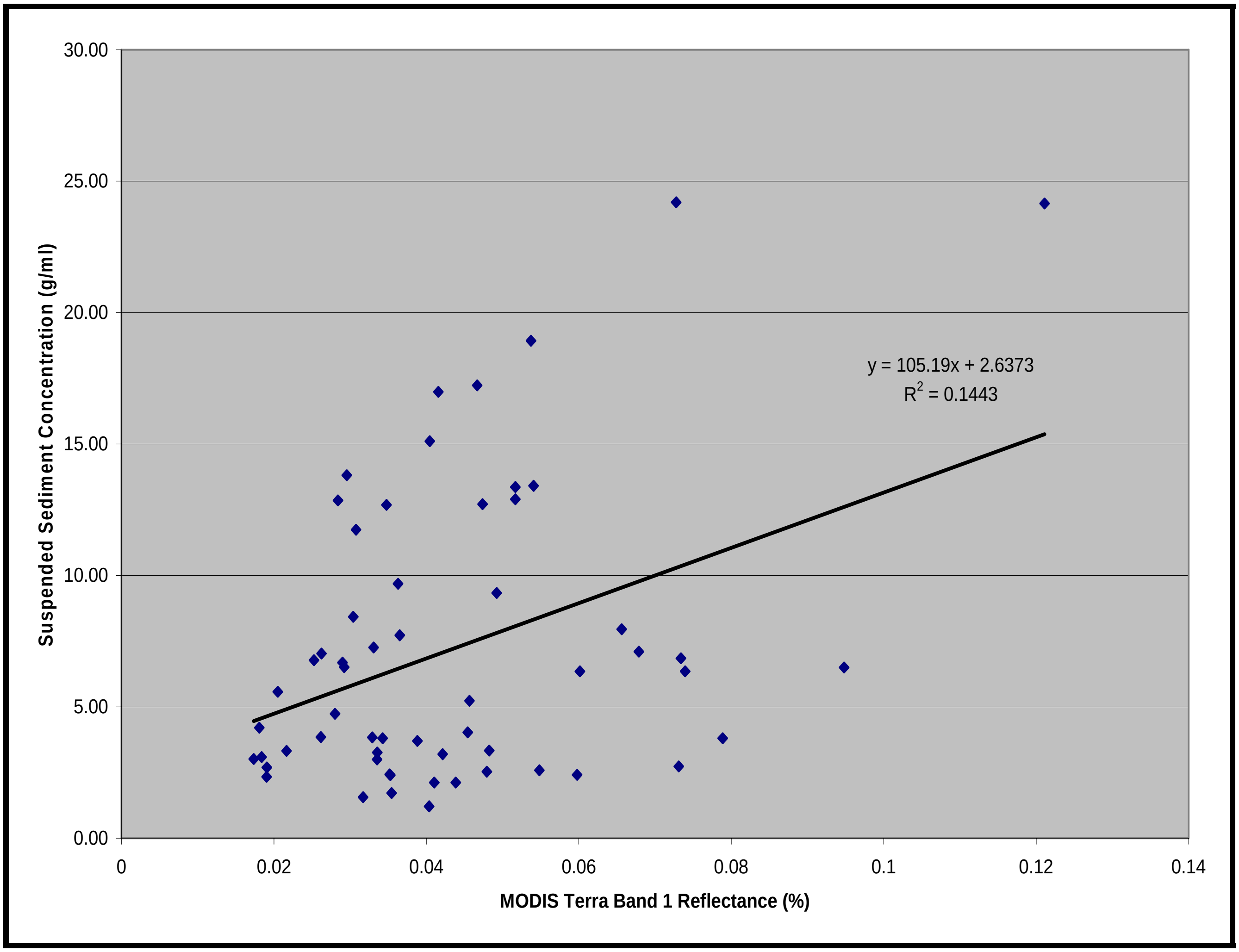


Figure 6: Relationship of suspended sediment concentrations as measured in the field and with MODIS Terra 250 m Band 1 from 2001-2006.

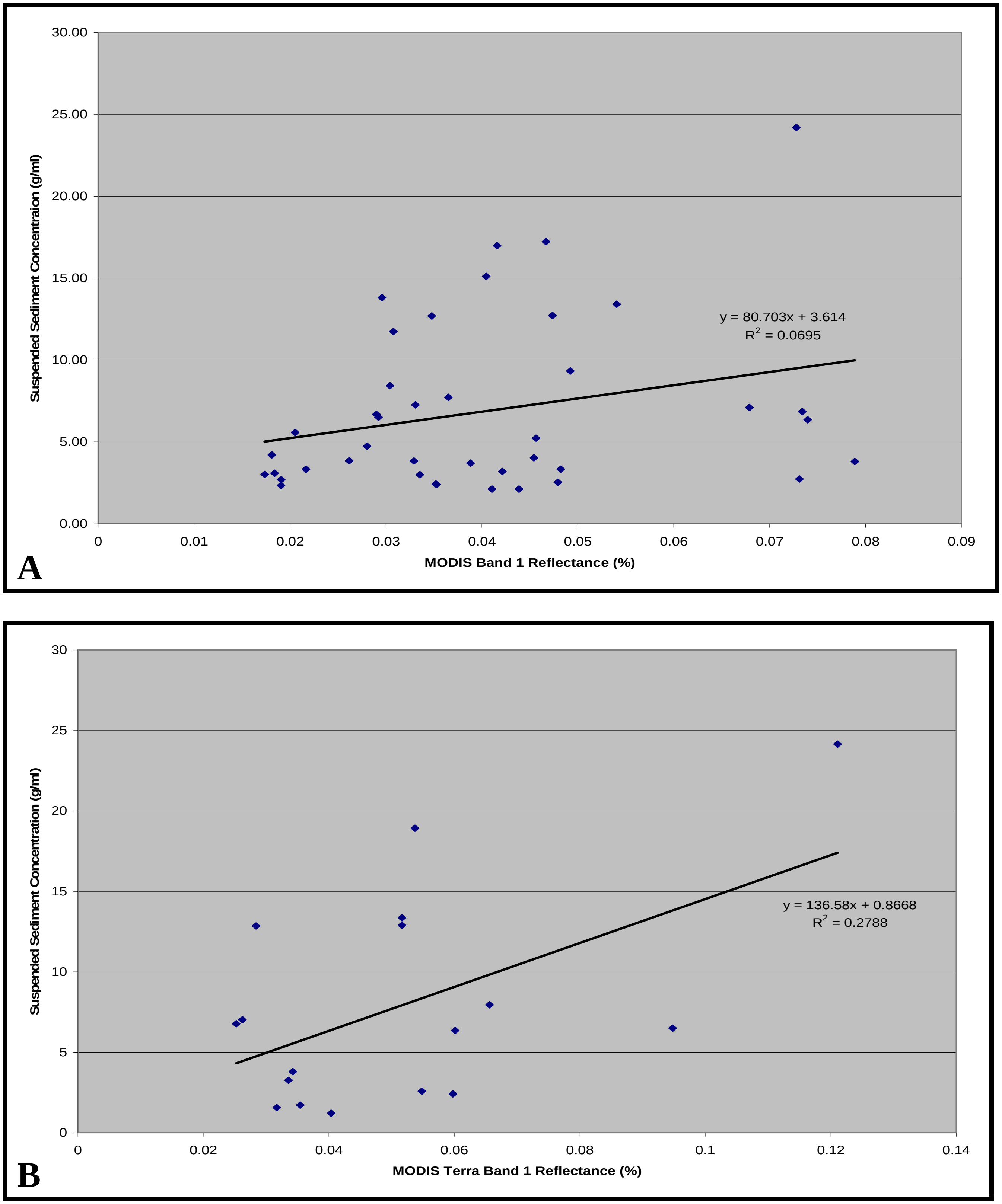
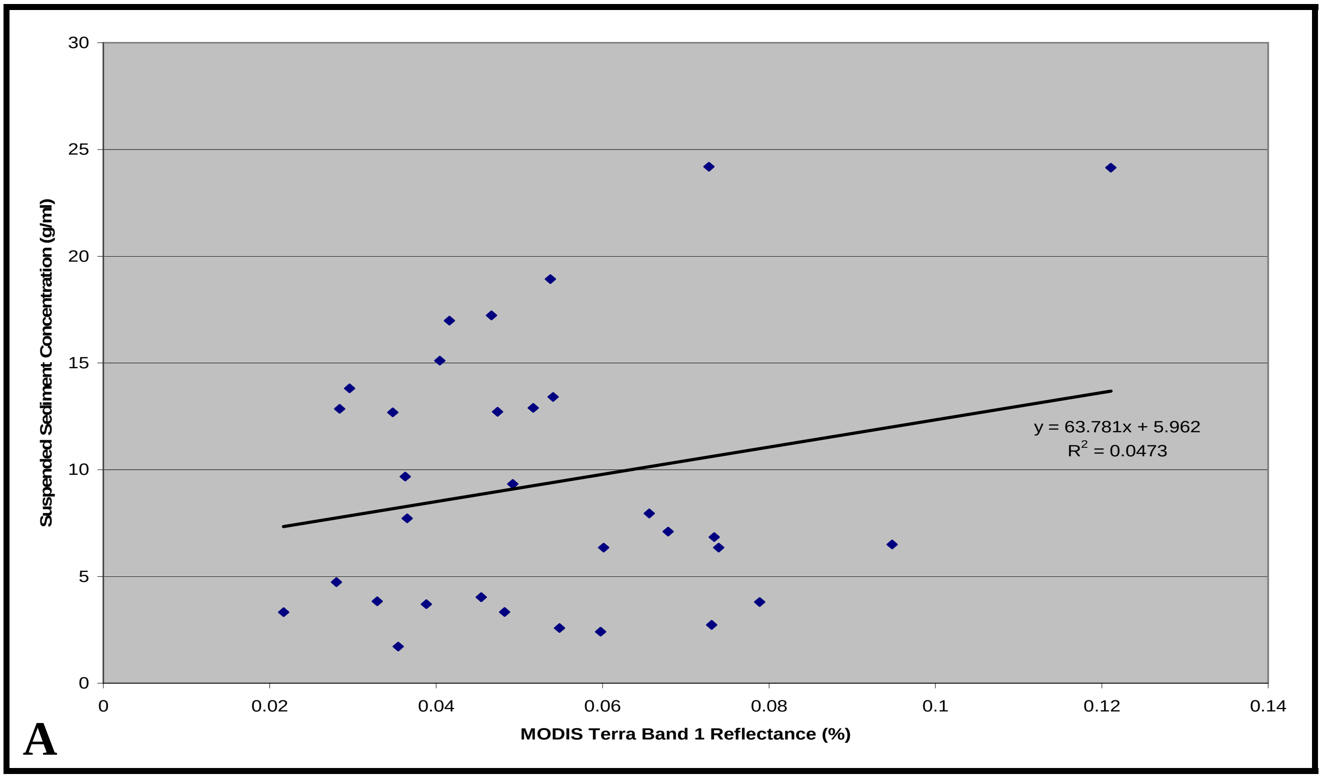


Figure 7: Relationship of suspended sediment concentrations as measured in the field and with MODIS Terra 250 m Band 1 from 2001-2006 (A: Dry Seasons; B: Rain Seasons).



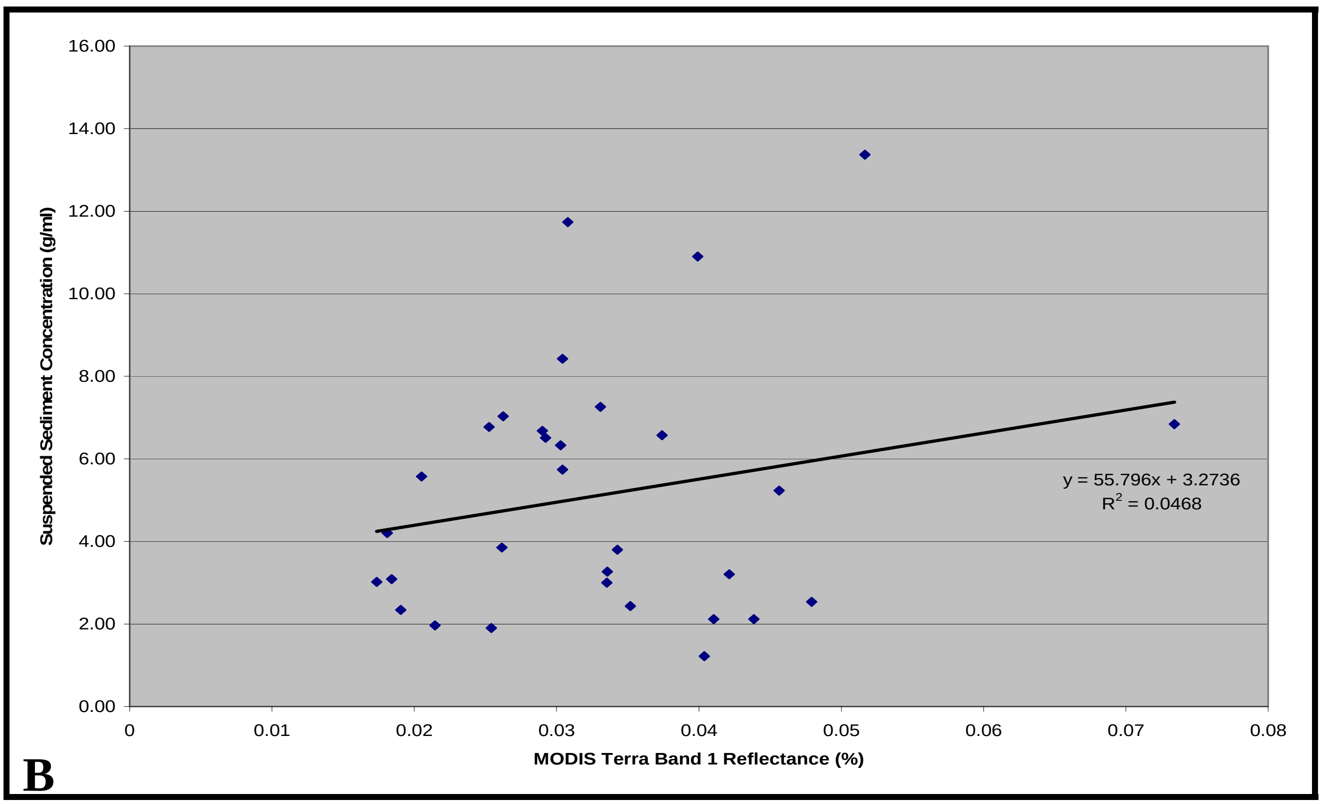


Figure 8: Relationship of suspended sediment concentrations as measured in the field and with MODIS Terra 250 m Band 1 from 2001-2006 (A: In-shore stations; B: Out-shore stations).

Discussion:

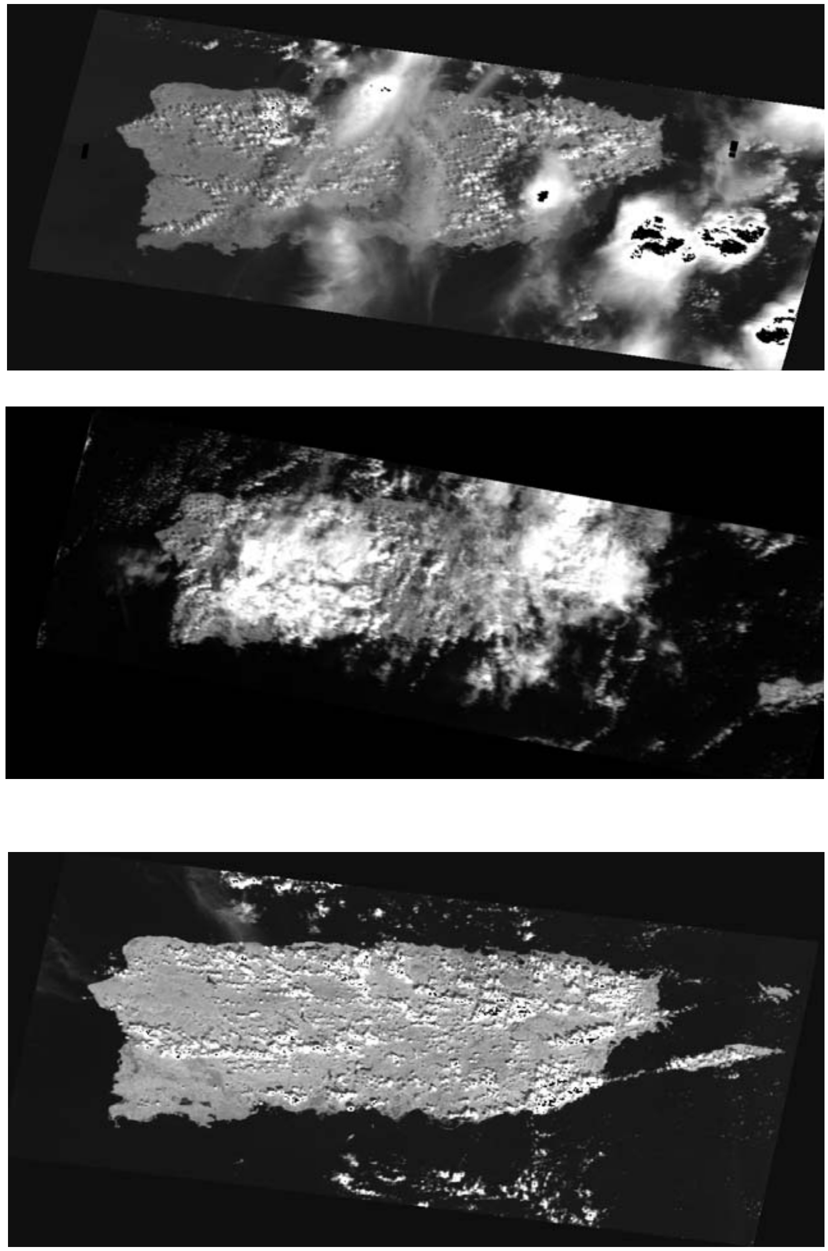
This project aimed to develop a site-specific algorithm for Mayagüez Bay using MODIS Terra sensor with Band 1 of 250 m of spatial resolution. Despite the various routines to analyze the relationship between suspended sediment concentration and water-leaving reflectance, none were fit to determine this properly. Some possible causes of error can be derived from the first part of this study. The greatest obstacle that has been confirmed is the effect of the atmosphere. It appears that despite the versatility and simplicity of Dark Subtract, the atmospheric influences are yet to be solved. Also, it is important to take into account that each scene appeared to have a peculiar response, as far as atmospheric effect goes (Figure 9). Another aspect that cannot be overlooked is the signal-noise ratio (SNR).

Some uncovered stations with low sediment concentration had a greater reflectance than higher concentrations of suspended material. The low correlation found in this study turns out to be inconsistent with certain studies of suspended sediments. Previous works have determined that both the radiance and reflectance generally increase at all wavelengths with increasing concentration of suspended solids (Figure 1). Also, the peak reflectance gradually shifts to longer wavelengths with increased concentrations. Nevertheless, very high concentration of sediments had little effect on reflectance. This is further demonstrated by a test that showed that at lower concentrations the upwelled reflectance increases at all wavelengths, having concentrations as low as 100 ppm becoming saturated at 450 and 550 nm. On the other hand, at the red wavelength of 650 nm and near infrared (750, 840, and 900 nm) it was found that the curves have a smaller slope with greater concentrations of suspended solids than at lower ones, but continue to show positive increases, as shown in Figure 10. (Witte *et al*, 1982). The reflectance values of suspended sediments found throughout Mayagüez Bay may be ruled by the effects explained above. Figure 11 show different properties of reflectance with varying suspended sediment concentration. Therefore, it is proven that higher concentrations of suspended sediments show higher reflectance. It is important to point out that the works discussed previously dealt with concentrations higher than those measured on Mayagüez Bay. The highest concentration ever recorded was 50.54, whereas the other studies had concentration greater than 100 ppm (or mg/l). There is the possibility that the lower amounts registered in Mayagüez Bay fail to emit a stronger reflectance signal.

Since most of the recorded scenes had different atmospheric effects, it is important to consider the implication of the routine that was used in this study, namely Dark-Pixel Subtraction. Currently, no robust atmospheric correction method exists for these effects (Shutler *et al*., 2007). On the other hand, Miller and McKee (2004) state that this method could be used for a wide variety of sky conditions and may be vulnerable to noise ratio effects. However, the task has been quite difficult for the Mayagüez Bay data. In contrast, some may argue the uses of this technique, claiming that it is quite crude. It assumes that the minimum reflectance in each band is zero, that the atmospheric correction can be modeled adequately as an additive effect, and that the correction remains constant. However, to some extent, visual inspection of an image can determine the validity of these assumptions (Rees, 2001).

The signal to noise (SNR) ratio may play an important role in the results of this study as well. Each sensor creates responses unrelated to target brightness (noise), created in part by electronic errors from various components of the device. This noise is not generated by the sensor alone. It could also be created in the atmosphere and interpretation processes. Therefore, in order to be effective, the sensor must be designed so that the noise levels are small relative to the signal. The desirable effect is one which SNR is large, not only for bright targets, but over dynamic ranges of the instrument, especially at lower levels of sensitivity (Campbell, 2002). MODIS bands 1 and 2 have SNR values as low as 128 and 209 respectably, for applications like land, cloud, and aerosol boundaries. On the other hand, SNR is higher in this sensor (ranging from 500 to 1000) for ocean color bands (MODIS Web).

Certain physical aspects can be visualized despite the low reliability of the algorithm found in this project. Coastal currents are the driving force in the transport and distribution of the shelf sediments. Their components in general circulation patterns at the Bay are wind-drift, wave-driven, tidal, and inertial components. However, regarding fine sediments, waves and tides are most influential. It has been determined that the surface layer and deeper current system transport and distribute the clays and silts brought by river runoff. There are seasonal fluctuations in rainfall that result in maximum river discharges from September through November and minimum flows in February and March. This variability can be seen on Figure 11. The sediments that Añasco, Yaguez, and Guanajibo rivers supply are terrigenous, derived from igneous rock environments and the reefs on the shelf margin provide biogenic material. However, only waves from the northwest contribute sufficient energy to the shelf to have an effect on sediment distribution. The longshore drift may be limited to the shallow nearshore areas of Añasco and Guanajibo rivers, but in their silt- and clay-laden plumes there is little mud deposition. Wave-induced turbulence is sufficient to cause continued suspension of these solids (Morelock et al, 1983). These dynamics may be encountered nowadays, having an unexpected effect on the reflectance response of suspended sediments.

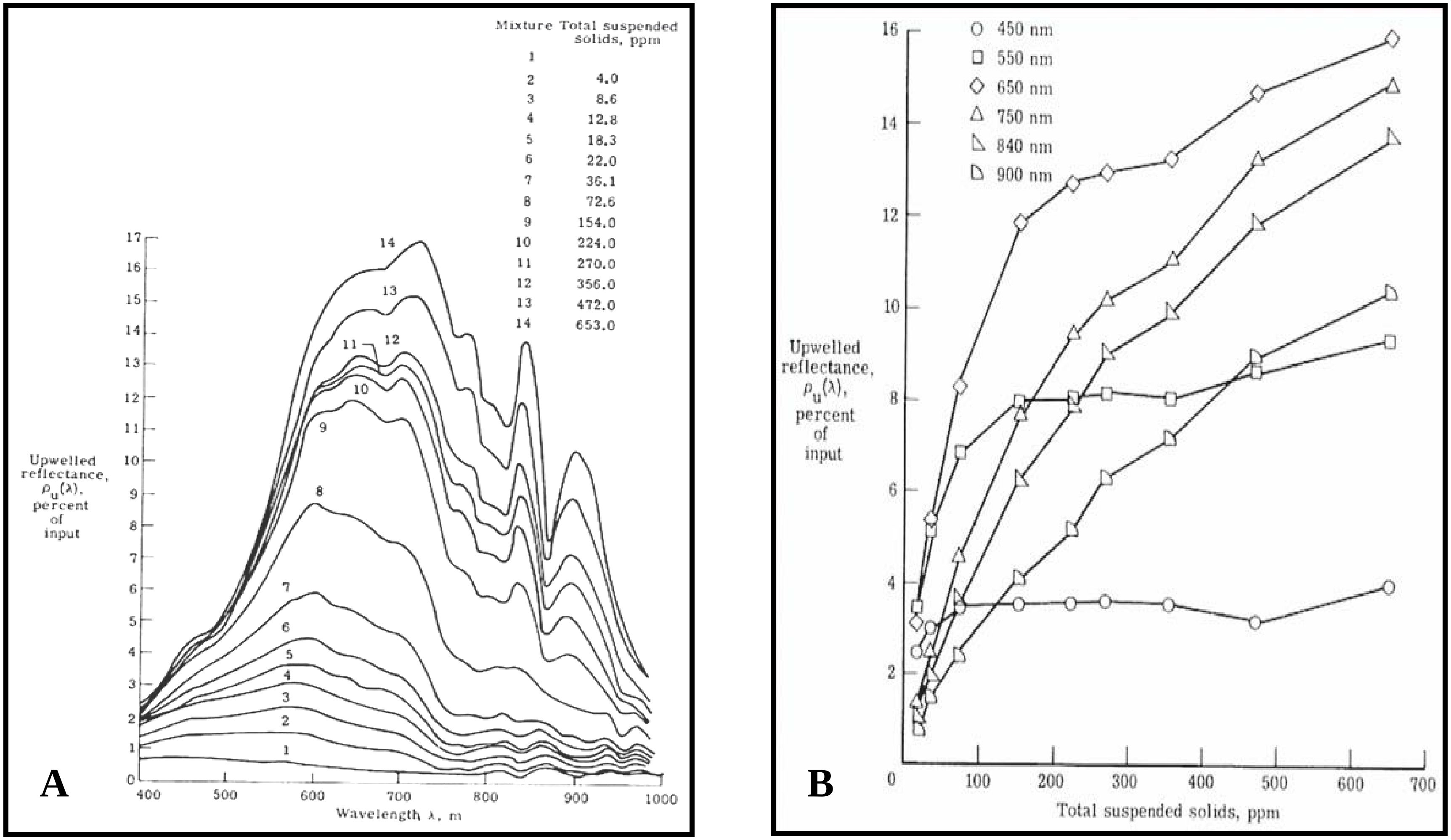


A

B

C

Figure 9: Geo-referenced images showing atmospheric conditions. (A: October 4, 2001; B: January 12, 2004; C: October 19, 2005).



1 ppm = 1 mg/ l

Figure 10: Relationships of suspended sediment concentrations as determined by Witte et al (1982). (A: Upwelled reflectance of water mixtures; B: Upwelled reflectance as a function of total suspended solids). *Note: 1 ppm = 1 mg/ l.*

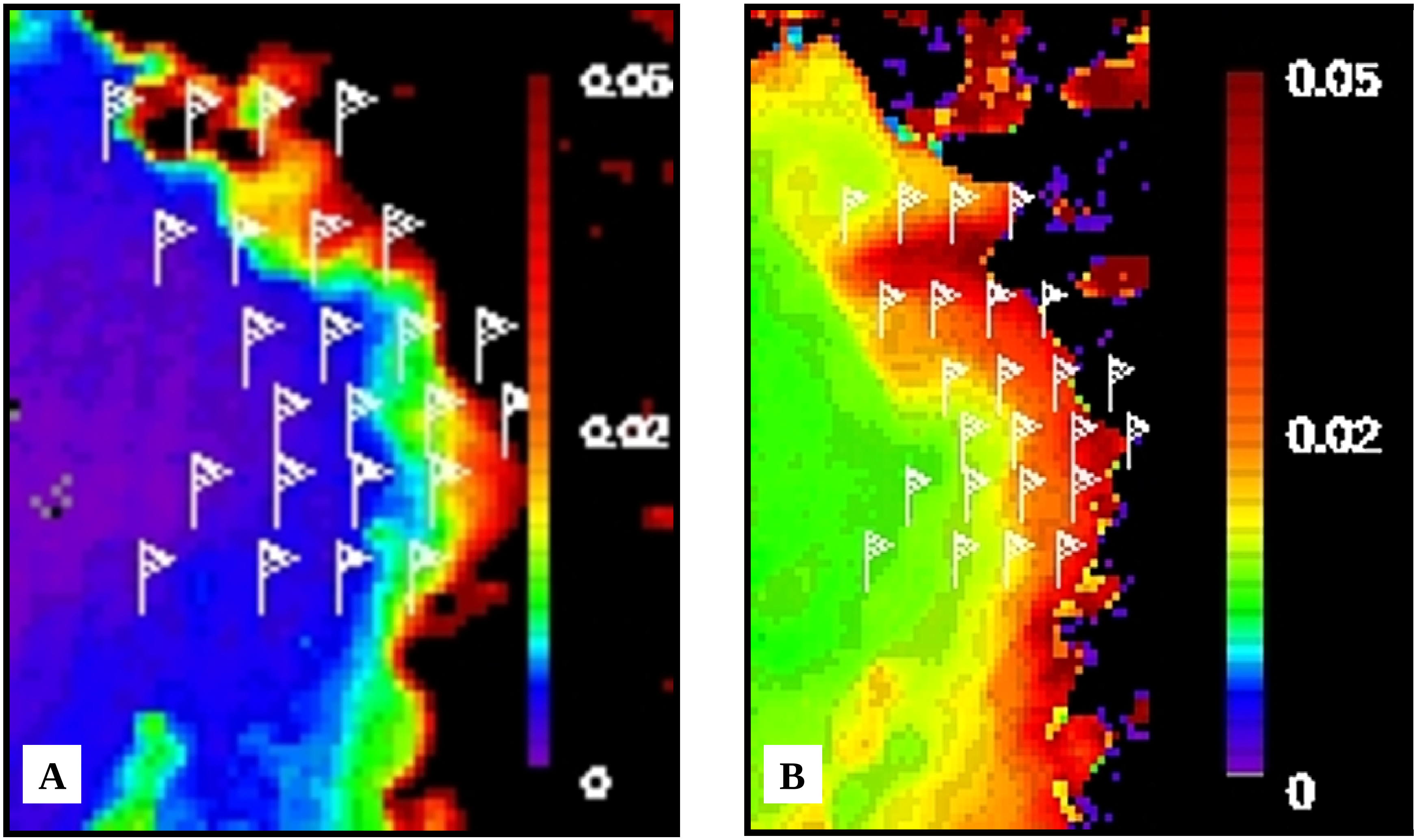


Figure 11: Examples of processed reflectance images derived from MODIS Band 1 at Mayagüez Bay. Dark areas represent land.
(A: February 12, 2004; B: October 19, 2005).

Conclusion:

The spatial and spectral resolutions of MODIS Terra 250 m Bands show that images can be generated with good quality standards, which can provide an extent of useful information. However, the application of this sensor in Mayagüez Bay, despite the earlier efforts, still proves to be a challenging task. It is recommended that a further study of the atmospheric conditions must be made in order to improve the quality of the derived reflectance. Furthermore, despite the useful and simple interface that ENVI 4.3 provides, it may be necessary to explore other image processing software programs such as HDFLook and its counterpart MSphinx, both developed by a joint effort between Laboratoire d'Optique Atmospherique, University of Maryland, and Distributed Active Archive Center. It is important to point out that these programs are somewhat complex, but they may turn out to be of great help.

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