FERNANDO GILBES' REPORT
(Performance period: October 1, 2006 to March 31, 2007)

1. RESEARCH COMPONENT
Thrust: Coastal Remote Sensing

- **Area of Research within the Thrust:** Bio-optical properties and ocean color
- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data.
- **Supervising PI or Co-Is**: Fernando Gilbes
- **Publications (during performance period):** Several articles are being prepared and will be ready to submission in summer 2007. The titles are:
  1. Spatial and Temporal Variability of Bio-optical Properties in Mayaguez Bay, Marcos A. Rosado, Fernando Gilbes, Roy A. Armstrong, and Jorge R. García
  2. Photosynthetic Parameters in Coastal Waters of Mayagüez Bay Influenced by River Discharge, Aurora M. Justiniano, Fernando Gilbes, and José M. López
  3. Empirical Models to Estimate Optical Parameters in Mayagüez Bay, Nazario D. Ramirez-Beltrán, Fernando Gilbes, and Joan Manuel Castro
  4. Bio-Optical Evidence Of Land-Sea Interactions in Mayaguez Bay, Fernando Gilbes, Marcos Rosado, Richard L. Miller, and Nazario Ramirez
  5. Variability of Colored Dissolved Organic Matter in Mayaguez Bay, Patrick Reyes, Fernando Gilbes, and Carlos Del Castillo
  6. Seasonality Of MODIS-Derived Ocean Color Patterns In Mayaguez Bay, William Hernandez, Fernando Gilbes, and Roy Armstrong
  7. Phytoplankton Abundance in Mayaguez Bay, Yvette Ludeña and Fernando Gilbes
  8. Role of Picoplankton in Mayaguez Bay, Jesús Lee, Fernando Gilbes, and Roy Armstrong
- Dollar amount of funds leverage with CREST funds:
  1. Effects of Rivers Discharge on the Spatial and Temporal Variability of CDOM and Cyanobacteria in Mayaguez Bay. Sponsored by UPRM-Research and Development Center. $2,500
  2. Monitoring Nutrients Content in the San Juan Bay Estuary using Hyperspectral Remote Sensing. Sponsored by Puerto Rico Water Resources and Environmental Research Institute. $21,200
  3. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000

Project Title: Bio-optical properties and remote sensing of Mayaguez Bay

- **Ongoing, New or Revised?**: Ongoing project
- **Staff:** None
- **Students PhD:** Patrick Reyes, Dep. of Marine Science
- **Students MS:** Vilmaliz Rodriguez (Dep. of Geology)
- **Students Undergraduate:** None
- **NOAA Collaborators:** Contact has been made with Dr. Richard Stumpf from NOAA. Dr. Stumpf is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a.
- **Other Collaborators:** Roy Armstrong (UPRM), Richard Miller (NASA), and Carlos Del Castillo (John Hopkins University)
- **Planned Project Duration**
  - **Start Date:** January 2007
  - **End:** December 2011
  - **Delayed to:** N/A
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** This project is helping to develop the necessary protocols for a most effective and low-cost way for monitoring coastal environments. The activities of this project also help to accomplish the important NOAA's goal of developing, valuing, and sustaining a world-class workforce by providing a research opportunity to undergraduate and graduate students.
- **Brief Narrative on Project Status:** A research cruise was performed in Mayaguez Bay during this report period (October 26, 2006). Discrete water samples were taken at two depths for Chromophoric Dissolved Organic Matter (CDOM), Total Suspended Solid (TSS), and Chlorophyll-a (Chl-a) at the same six previously established stations. Absorption coefficient of CDOM (ag) and its spectral slope (S parameter) were calculated at five wavelength ranges 250-300, 300-350, 375-400, 412-443 and 400-500 nm. During the processing of this cruise data, errors were observed in the salinity and temperature profiles. Therefore, this data set will not be included in our GIS database. Major processing and analyses of collected data was also carried out for developing the GIS. This includes salinity temperature, fluorescence, absorption, attenuation, backscattering, chlorophyll-a, suspended sediments, and CDOM. Data collected from 2001 to 2006 was added to ArcGIS and thematic maps were created by different depths. The results continue supporting the direct relationship between river discharge and bio-optical measurements. These new analyses are being used to develop new site-specific algorithms. Since the spaceborne ocean color sensors (i.e. SeaWiFS and MODIS) are not giving good results a new approach is planned. The collected data will be used to generate an algorithm for the GER-1500 field spectroradiometer.
- **Operational Impact**: The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.

2. EDUCATION COMPONENT

Patrick Reyes presented his work during a Symposium of Mayaguez Bay organized by the Center for Hemispherical Cooperation (CoHemis). It was held in UPRM during March 16, 2007 and over 75 people participated.

3. OUTREACH COMPONENT

Several talks of our work were presented during the CoHemis Symposium about the Mayaguez Bay and people from different sectors of the society participated and learned about the findings of our project.

4. Appendices: Sub-projects descriptions

Sub-project #1: Dynamics of Chromophoric Dissolved Organic Matter (CDOM)
BY: Patrick Reyes-Pesaresi

During this fall-spring season we did a cruise to the Mayagüez Bay in October 2006 (rainy season). At our six previously established stations, discrete water samples were taken at two Depth for Chromophoric Dissolved Organic Matter (CDOM), Total Suspended Solid (TSS), and Chlorophyll-a (Chl-a). With the optical density measured for CDOM, absorption coefficient (a_g) and the spectral slope (S parameter) were calculated at five wavelength ranges 250-300, 300-350, 375-400, 412-443 and 400-500 nm). During the processing of the October cruise, ancillary data errors were observed in the salinity and temperature profiles for some of the sampled stations. We decided that the data set for that month would be left out of the data set. Since the temperature and salinity measurements are necessary for the total absorption and attenuation corrections taken with the Ac-9. At this moment the only data left to be processed is for the first eight cruises (between 2001-2004; Table 1), for the profiles generated by the bio-optical Rosette. The rest of the collected data for CDOM, TSS and Chl-a samples have been arranged in it's Excel sheets waiting for the further processing of the cruise station profiles that will be used in the correlations analysis.

In January we reprocessed all the calculated spectral slopes (S) at five wavelengths intervals for all 18 previously processed cruises, since and error was found in one of the macros used. The spectral slopes were then added to the data set and used to re-calculate the correlations were they were used in the case the last eleven cruises. Also in January the precipitation data that was shared with us by Dr. Eric Harmsen, was processed by taken the data that will be useful for our time study period (2001-2006). Other precipitation data taken with other rain gauges located in the water shed for our rivers of interest and not included in (Dr. Harmsen data set) was incorporated by using the Puerto Rico and the U.S.Virgin Island Climatological Center at UPR at Mayagüez. We hope to use this data for future modeling River Discharges during our sampling cruise for Yagüez River, since this river lacks an USGS steam flow monitoring station. River discharge data was obtained form the USGS web page Stream flow discharge for the gauges located nearer to the cost in these case the Añasco River located at Guacio and the Guanajibo River located at Hormigueros. The data gathered for the last eleven cruises (2004-2006) was further processed calculating the average discharge by month and was later graphed showing the characteristic Rainy and Dry season that was used to separate our seasons.

The data gathered for two previously un-worked cruises data set, one for the AVIRIS mission on August 17, 2004 with 10 stations and other for March 10, 2005 with six stations, were processed by a student during the month of March. The resulting profiles were later organized and the data of interest was later extracted for the measured parameters. The resulting data was then incorporated to the previous generated correlation graphs between the different measured parameters finding very poor correlations between all parameters during the dry season, and some very good correlation during the Rainy season between salinity vs. TSS, Salinity vs. CDOM a_g 375, and a_g 412 nm and salinity vs. Chl-a only at depth. Other correlations using salinity vs. chl-fluorescence were performed and were very similar to the one calculated with the measured chl-a concentration in the laboratory.

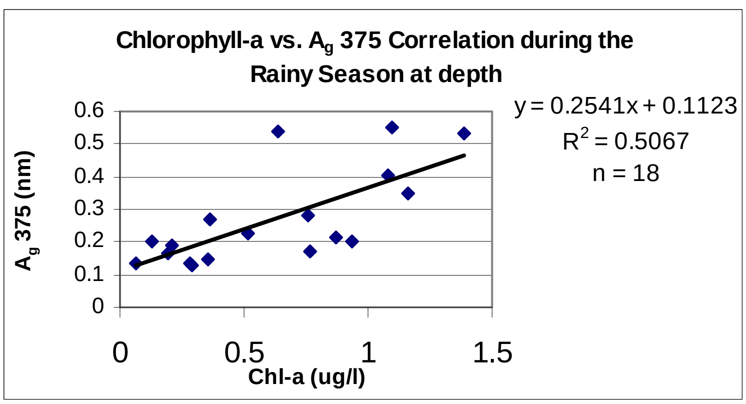
During the month of March a mini symposium on all the works done on the Mayagüez Bay in the last 15 years hosted by Dr. Fernando Gilbes and sponsored by CoHemis that was held the 16 of March at UPR-Mayagüez. There we had a 20 minute presentation Titled: "Variabilidad de la Materia Orgánica Disuelta Cromofórica (MODC) en la Bahía de Mayagüez", were we presented some very preliminary results of our research.

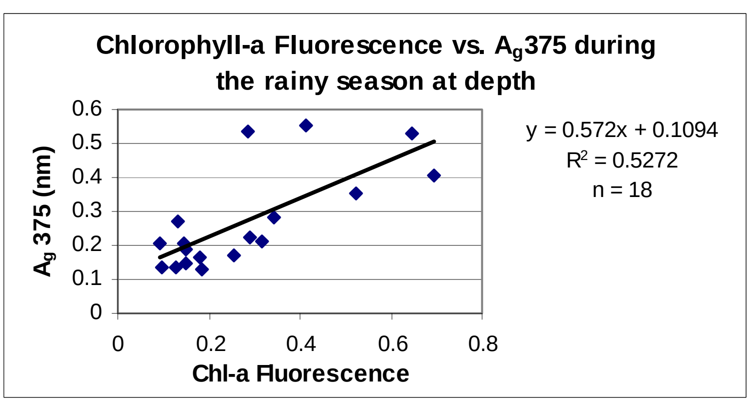
At this moment we are waiting for the arrival of the Bio-optical Rosette annual calibration checkup. Right now we are planning a cruise that will take two day, and will take place during the month of April 2007 dry season. For this cruise we expect to do our usual stations with vertical profiles and other water samples measurements (CDOM, TSS, and Chl-a) on day one. The next day the instruments will be fixed in an continuous recording mode (flow through system) that will measuring only parameters at the surface, also we will be taking water samples for CDOM, TSS, and Chl-a along a curse in the Bay. This data will be used to crate a 3D maps for salinity, temperature, CDOM, TSS and Chl-a also Ac-9 total absorption and attenuation will be used.

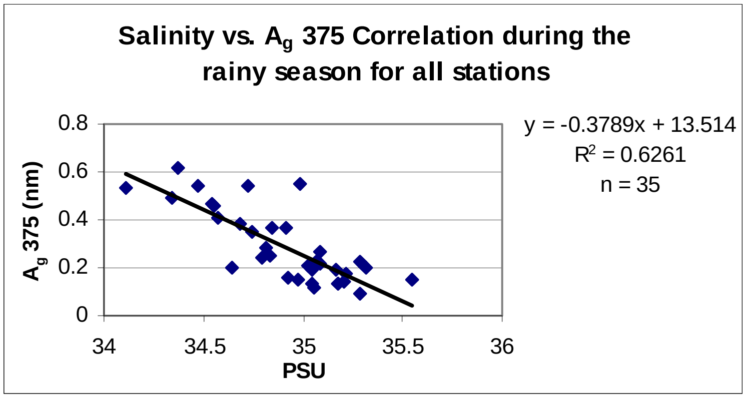
During the month or April I will be taking my comprehensive exam and I am also working in a paper on the variability of CDOM in the Mayagüez Bay.

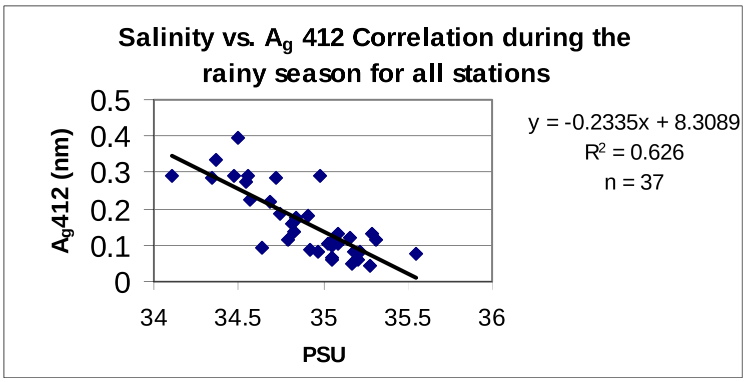
Table: 1 Data that have been processed for all the cruises made to date.

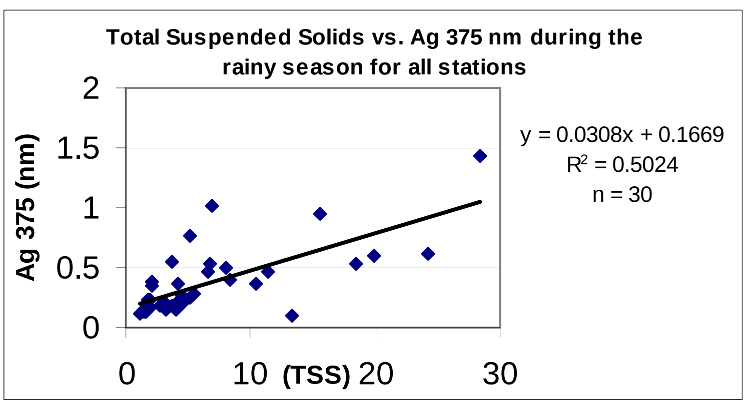
Date	CDOM Rossette	Ag CDOM	Spectral Slope	Salinity	Sediments	Chl-a	Rrs
April 24-26 2001	No	Yes	Yes	No	Yes	Yes	Yes
October 2-4 2001	No	Yes	Yes	No	Yes	Yes	Yes
February 26-28 2002	No	Yes	Yes	No	Yes	Yes	Yes
August 20-22 2002	No	Yes	Yes	No	Yes	Yes	Yes
February 25-27 2003	No	Yes	Yes	No	Yes	Yes	Yes
October 7-9 2003	No	Yes	Yes	No	Yes	Yes	Yes
January 12-14 2004	No	Yes	Yes	No	Yes	Yes	Yes
February 12 2004 ATLAS	No	Yes	Yes	No	Yes	Yes	Yes
August 17 2004 AVIRIS	Yes	Yes	Yes	Yes	Yes	Yes	Yes
March 10 2005	Yes	Yes	Yes	Yes	Yes	Yes	Yes
July 19 2005	Yes	Yes	Yes	Yes	Yes	Yes	Yes
August 17 2005	Yes	Yes	Yes	Yes	Yes	Yes	Yes
September 20 2005	Yes	Yes	Yes	Yes	Yes	Yes	Yes
October 19 2005	Yes	Yes	Yes	Yes	Yes	Yes	Yes
December 6 2005	Yes	Yes	Yes	Yes	Yes	Yes	Yes
March 8 2006	Yes	Yes	Yes	Yes	Yes	Yes	N/D
April 21 2006	Yes	Yes	Yes	Yes	Yes	Yes	Yes






Salinity vs. A_g 375 Correlation during the rainy season for all stations
y = -0.3789x + 13.514
R^2 = 0.6261
n = 35
A_g 375 (nm)
0.8
0.6
0.4
0.2
0
34
34.5
35
35.5
36
PSU


Salinity vs. A_g 412 Correlation during the rainy season for all stations
y = -0.2335x + 8.3089
R^2 = 0.626
n = 37
A_g412 (nm)
0.5
0.4
0.3
0.2
0.1
0
34
34.5
35
35.5
36
PSU


Total Suspended Solids vs. Ag 375 nm during the rainy season for all stations
y = 0.0308x + 0.1669
R^2 = 0.5024
n = 30
Ag 375 (nm)
2
1.5
1
0.5
0
0
10
(TSS)
20
30

Sub-project #2: GIS Database of bio-optical properties
By: Vilmaliz Rodríguez-Guzmán

One of the objectives for this period was to start a spatial and temporal analysis of different Bio-optical properties in Mayaguez Bay. This approach was made using GIS tools, which allow the import of spatially referenced quantitative data for this type of analysis. The data used on part of the study included measurements collected since July 2005 to March 2006 during 9 research cruises. A total of eight stations distributed along the Mayagüez bay are visited during these cruises for bio-optical measurements (Fig. 1), where six of them are monitored for Total Suspended Solids (TSS). Varieties of interpolation probabilities are enormous, therefore the interpolations made include the most representative examples. The results presented on this report are focus on interpolations based on measurements of salinity (psu), chl-a fluorescence, TSS (mg/l), ag412 (nm) and bb620 (nm).

The second objective was to start a new processing procedure to prepare the entire rosette data collected since April 2001. This procedure consists on apply various routines to the files logged by the rosette to finish with a simple file ready to use for analysis. Data from eleven of nineteen cruises have been processed and the effort continues.

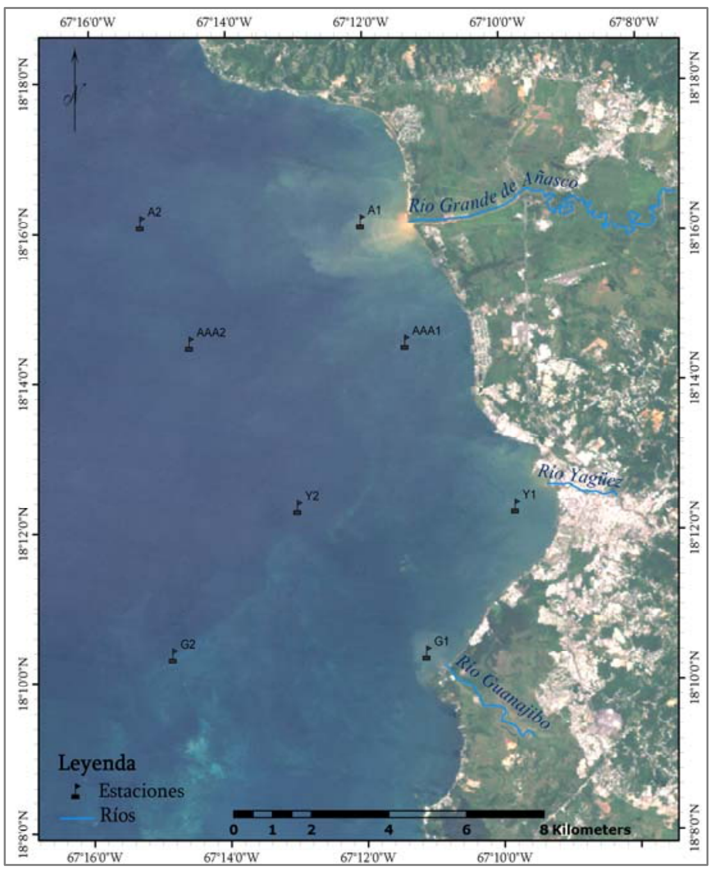


Figure 1. Study area with the stations visited during the research cruises

Methodology

Different software is used for the procedure of the rosette data preparation. The first step consists on use WAP (version 4.10) to take the raw files and calibrates them and produces ASCII files. These files are then open is Excel (Microsoft Office, 2003) to eliminate warming-up and up-cast measurements, which are not used in our analyses. Subsequently, various pre-defined routines are run in SBE (version 5.37e). The routines used in this process are: ASCII in, Filter, Wild Edit, Window Filter and Bin Average.

Mean values of October and September 2005 cruises were calculated to represent the rainy season, while the same method was applied to the months of March and April 2006, this time to represent the dry season. March 2006 presented a problem with one of the instrument (ac-9) in A1 station, therefore single April's measurements for this station were used to represent the dry season. In addition, during April 2006 research cruise station G1 could not be visited and therefore the measurements presented on the dry season for this station consists only of March data.

The 3D analyst extension of ArcGIS 8.3 (ESRI, 2002) was the tool used to produce the interpolations. This extension has four interpolation methods: Inverse Distance Weighted, Spline, Kriging and Natural Neighbors. Interpolation tests were made using all the methods and the results were not significantly different. The selected method for our analysis was Spline, which is a general-purpose interpolation method that fits a minimum-curvature surface trough the input points (ESRI, 2002). We decided to use this method because its description fits to our data, and this was the interpolation method used in similar previous work.

Results and Discussion

The majority of the interpolations showed marked differences between rainy and dry season. In general, salinity is higher and relatively homogeneous along the Bay during the dry season (Fig. 2) and spatial changes are more distinguishable in the rainy season (Fig. 3). The salinity results showed changes in intensity of fresh water input, which can be associated with changes of other parameters.

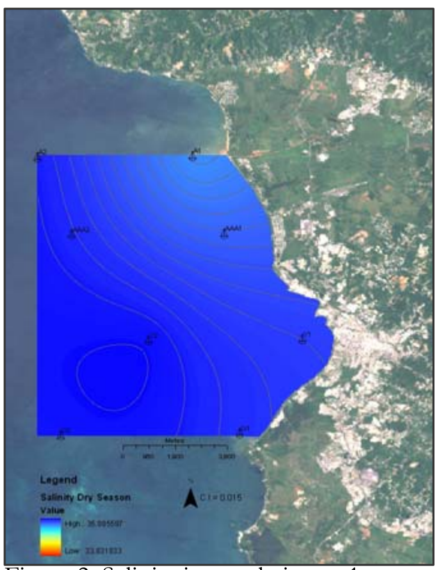


Figure 2. Salinity interpolation at 1 meter during dry season

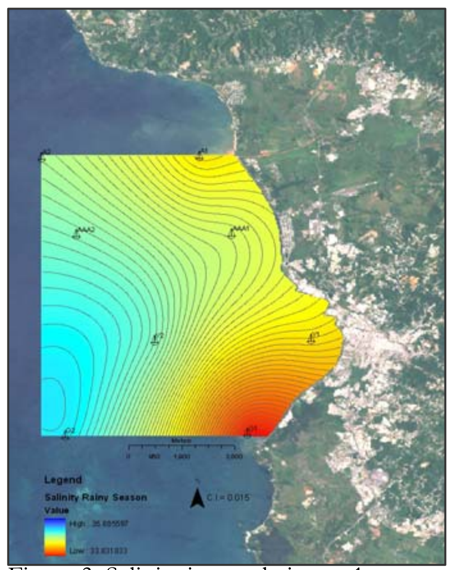


Figure 3. Salinity interpolation at 1 meter during rainy season

Higher values of chlorophyll-a fluorescence were concentrated near the Grande de Añasco R. plume during the dry season (Fig. 4) and near the Guanajibo R. plume during the rainy season (Fig. 5). A relative comparison was made using our fluorescence values and the chl-a measurements of March, April, September and October 1990 (Gilbes et al., 1996). In both seasons (dry and rainy), maximum values of chlorophyll-a fluorescence occurred at inshore stations, as published results by Gilbes et al., 1996. On the other hand, temporal changes observed are slightly different to the published results. During 1990 dry and rainy season (equally defined to the present study) chl-a values remained higher in the Añasco R. station compared to the Guanajibo R. station. In our analysis, the chl-a fluorescence was higher in the Gunajibo R. area than in the Añasco R. area during the dry season. Besides, in our results the Yagüez R. area presented higher chl-a fluorescence values during the rainy season than observed throughout dry season, and this change in not detected in 1990 data (Gilbes et al., 1996). These discrepancies can be explained with difference in data nature and inter-annual variations.

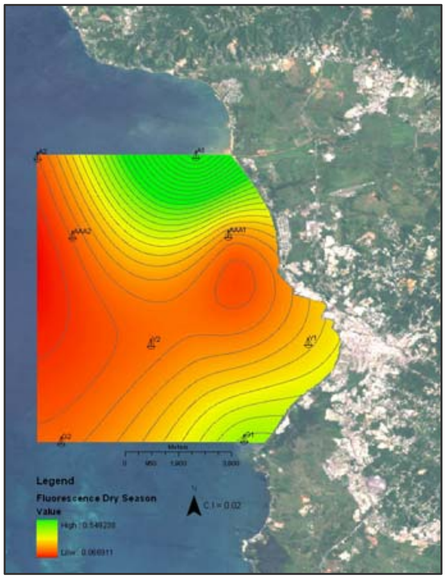


Figure 4. Fluorescence interpolation at 1 meter during dry season

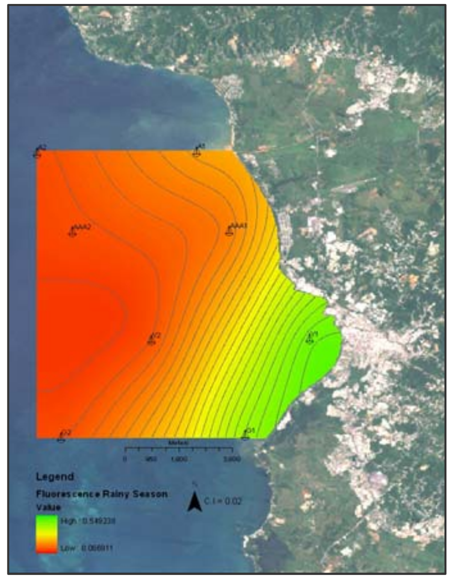


Figure 5. Fluorescence interpolation at 1 meter during rainy season

Another parameter interpolated was backscattering at 620 nm (bb620), which is one of the wave lengths measured by the Hydroscat6. The bio-optical properties of bb620 suggested that this parameter can be use to estimate TSS, therefore is a very important parameter for the project. The temporal analysis shows an inverse relationship with chl-a fluorescence during the dry season (Fig. 6 & 7). Increases in water turbidity affect light input and consequently, productivity. High values during the dry season at Guanajibo station were attributed to wave and current-driven processes like re-suspension. This phenomenon has been observed in several studies (Morelock, 1983; Miller et al., 1994) and is expected to have and important influence in our results.

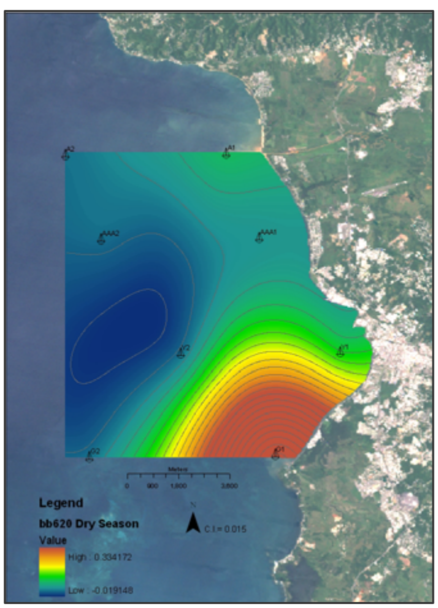


Figure 6. bb620 interpolation at 1 meter during dry season

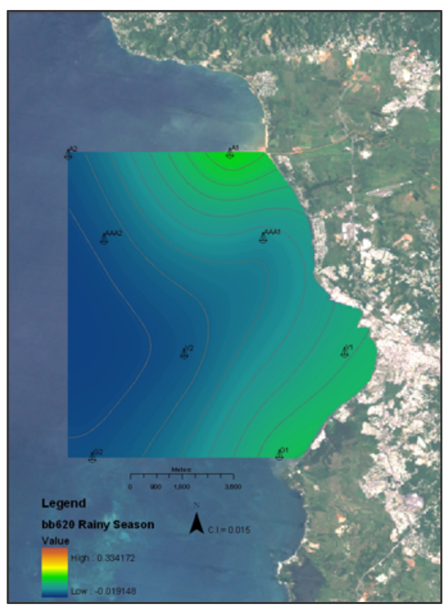


Figure 7. bb620 interpolation at 1 meter during rainy season

We also were interested on identified possible spatially and temporally changes of TSS along the 6 stations monitored for this parameter (A1, A2, AAA1, Y1, G1 and G2). No marked differences were observed between rainy and dry season (Fig. 8 & 9). Slight augment of TSS is observed near the Guanajibo river discharge area during the dry season, which can be explain, as we did with bb 620, with re-suspension events. In general, both diagrams show higher values near Añasco and Guanajibo river plumes, where the higher quantity of TSS is appearing to occur at the south part of the bay.

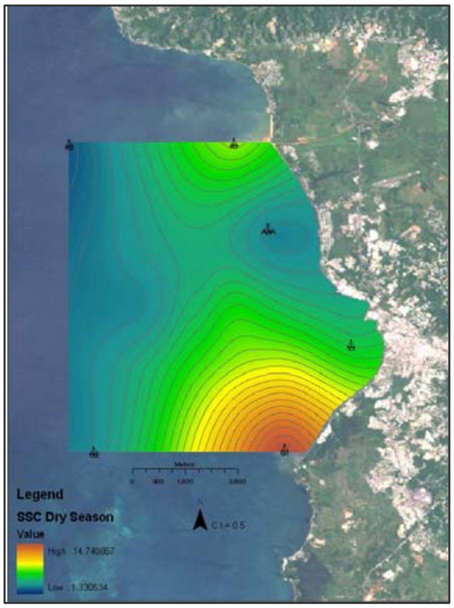


Figure 8. TSS interpolation at 1 meter during dry season

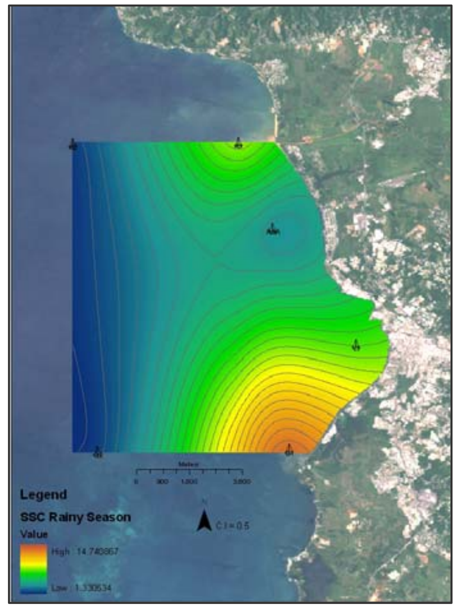


Figure 9. TSS interpolation at 1 meter during rainy season

Different plots were made to summary the existing TSS data and to establish possible correlations between TSS variations and discharge magnitude of the rivers. First, we wanted to see how the TSS values change trough time (Fig.10). The plot does not presented any significant trend, some moments stations behave similar, and others show an opposite trend. The discharge information comes from the USGS gauges of Grande de Añasco R. and Guanajibo R., specifically the ones located nearest to the coast. The discharge values used for the correlations represent the mean discharge of the sample day and the day before. Correlations of discharge information of the two rivers and the TSS in the three coastal stations (associated with rivers) were made (Fig.11 & Fig.12) and no significant relationships were detected.

All the results presented on this report are preliminary because a new correction and quality control process is being applied to all the data.

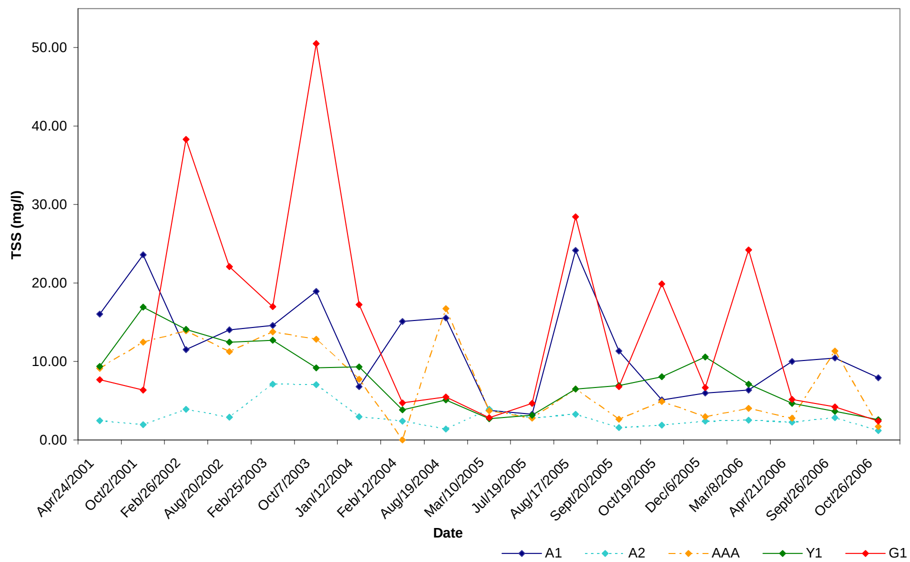


Figure 10. Total Suspended Solids (TSS) in five stations through

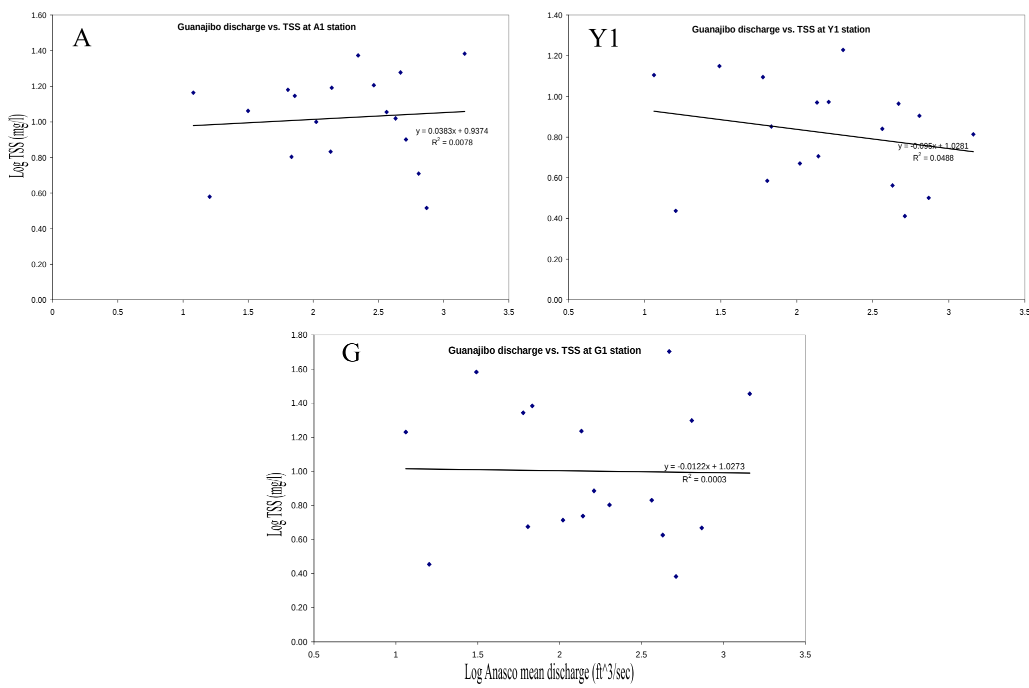


Figure 11. Relationship between TSS measured in A1, Y1 and G1 stations and Añasco R. mean discharge (sample day and day before) reported by USGS.

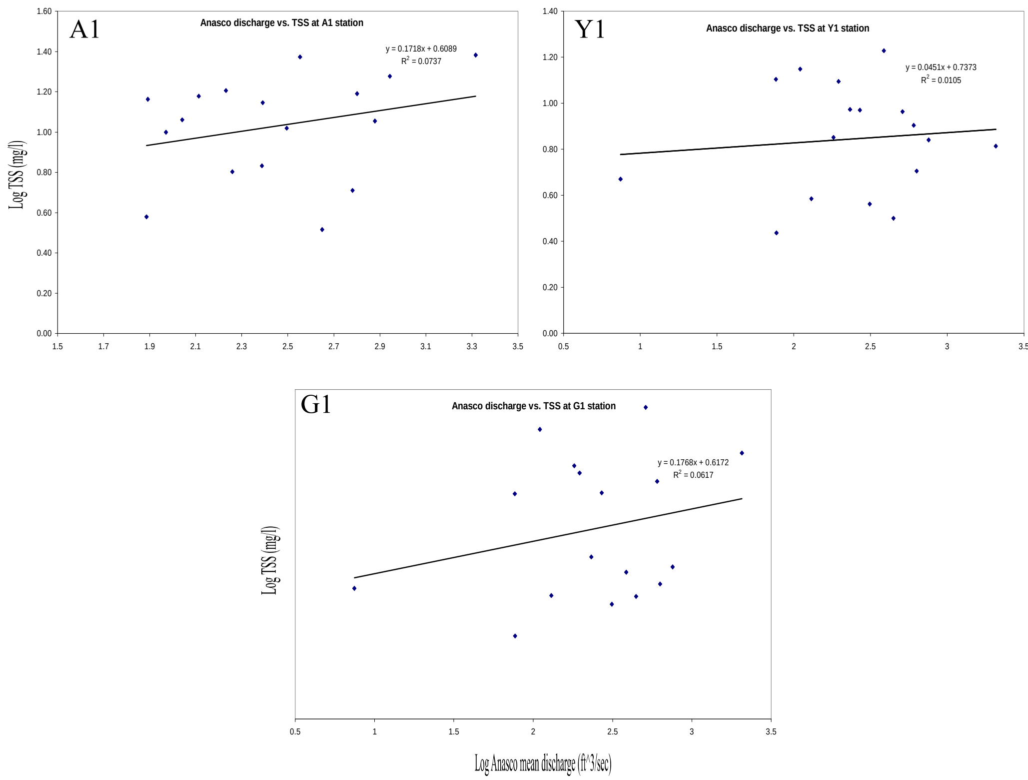


Figure 12. Relationship between TSS measured in A1, Y1 and G1 stations and Guanajibo R. mean discharge (sample day and day before) reported by USGS.

References:

ESRI, 2000-2002. Using ArcGIS 3D Analyst (ArcGIS 8.3 user manual), p.72-75

Gilbes, F., López, J.M., Yoshioka, P.M., 1996. Spatial and temporal variations of phytoplankton chlorophyll α and suspended particulate matter in Mayagüez Bay, Puerto Rico. Journal of Plankton Research, 18 (1), 29-43.

Miller, R.L., Cruise, J.F., Otero, E., López, 1994. Monitoring Suspended Particulate in Puerto Rico, 30(2), 271-283.

Morelock, J., Grove, K., Hernández, M.L., 1983. Oceanography and patterns of shelf sediments Mayagüez, Puerto Rico. Journal of SedimentaryPetrology, 53(2), 0371-0381.

COASTAL –GILBES' GROUP REPORT
(Performance period: April 1, 2007 to August 31, 2007)

RESEARCH COMPONENT

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):** A journal publication is now in preparation and it will be submitted before the end of 2007. This paper is related with the work done with suspended sediments and the backscattering coefficient. The journal has not been selected yet, but there are several possibilities like Applied Optics or Remote Sensing of Environment. Also, it has been decided to write a peer-review book about all the oceanographic work done in the past ten years in Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.
- **Dollar amount of funds leveraged with CREST funds (during performance period):**
  1. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
  2. Monitoring Nutrients Content in the San Juan Bay Estuary using Hyperspectral Remote Sensing. Sponsored by Puerto Rico Water Resources and Environmental Research Institute. $5,000
  3. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $50,000
- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None

- **Students PhD:** Patrick Reyes, UPRM-Department of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** José Martinez, UPRM-Department of Geology (this student worked in a NOAA CREST related topic as part of the course Geol 4049, undergraduate research; but he was not directly funded)
- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a. A possible visit of Vilmaliz Rodriguez to his laboratory will be planed and coordinated for the future.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences)
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Validation of MODIS data in Mayaguez Bay was continued. Estimates of Suspended Sediments using bands 1 and 2 (250 m) and Richard Miller's algorithm were compared with field measurements. The first version of site-specific algorithms have also been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. The standard algorithm developed and used by NASA to estimate Chl-a using MODIS was tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data.

Tasks (For year I as per the Milestone Chart)

Task (1) Compare to satellite water leaving products and atmosphere retrievals

The high spatial and temporal resolution of MODIS was evaluated in Mayaguez Bay. The work also tested the algorithm developed by Miller and McKee (2004) to measure suspended sediments using Band 1. Measurements of suspended sediments were obtained from field samplings between 2001 and 2006 at different stations in Mayagüez Bay. Then, several MODIS images were obtained from the NASA Active Archive Center for the same dates of field measurements. The selected images were atmospherically corrected using Band 2 and the Dark Pixel Subtraction method as suggested by Miller and McKee (2004). After this preprocessing the algorithm for suspended sediments was applied to Band 1. Finally, the MODIS estimates were compared with the field data. It was found that suspended sediments estimated from the images were much higher than field measurements. The tested algorithm gave a low average correlation value (R^2 = 0.0845). This shows that despite the relative good spatial resolution of MODIS Band 1 (250 m) the relationship from the algorithm was inconsistent throughout the studied area. The work demonstrates that a site-specific algorithm is needed to better estimate suspended sediments in this area using MODIS. More information can be found in the appended report of Jose Martinez.

Task (2) Intercomparison of the below/above water signals with aircraft and satellite data as available.

A two-day cruise was performed during May. In the first day 8 stations were sampled. During the second day the bio-optical package was mounted in a continuous flow mode. The collected data will be used to generate bio-optical maps using ArcGIS. During the same days water samples for CDOM, Chl-a, and TSS analyses were collected in the estuarine area of the three rivers using a kayak. On the other hand, the rain gauges located in the watershed of the rivers were downloaded for January 1, 2004-June 30, 2007 from the NWS web page. Data for river discharge was also downloaded from the USGS database, except for the Yagüez River. These data were correlated with the bio-optical data collected during the same time period. The analyses demonstrate that the distance between the USGS stations and the rivers mouth is important. Since the station of the Guanajibo River is closer, it gave better correlations than those in the Añasco River because its station is more far away. This is crucial for future development and application of land-sea interface models. More information can be found in the appended report of Patrick Reyes.

Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):** A journal publication is now in preparation and it will be submitted before the end of 2007. This publication is related with the work done with suspended sediments and the backscattering coefficient. The journal has not been selected yet, but there are several possibilities like Applied Optics or Remote Sensing of Environment. Also, it has been decided to write a peer-review book about all the oceanographic work done in the past ten years in Mayaguez Bay, including all the

work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.

- **Dollar amount of funds leveraged with CREST funds (during performance period):**
  1. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
  2. Monitoring Nutrients Content in the San Juan Bay Estuary using Hyperspectral Remote Sensing. Sponsored by Puerto Rico Water Resources and Environmental Research Institute. $5,000
  3. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $50,000
- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Patrick Reyes, UPRM-Department of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** José Martinez, UPRM-Department of Geology (this student worked in a NOAA CREST related topic as part of the course Geol 4049, undergraduate research; but he was not directly funded)
- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a. A possible visit of Vilmaliz Rodriguez to his laboratory will be planed and coordinated for the future.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences)
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Validation of MODIS data in Mayaguez Bay was continued. Estimates of Suspended Sediments using bands 1 and 2 (250 m) and Richard Miller's algorithm were compared with field measurements. The first version of site-specific algorithms have also been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. The standard algorithm developed and used by NASA to estimate Chl-a using MODIS was tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data.

Tasks (For year I as per the Milestone Chart)

Task (1) Analysis of optical field measurement together with Chl, TSS concentrations

A relationship between the backscattering coefficient (b_b), remote sensing reflectance (R_{rs}) and total suspended sediments (TSS) was developed for Mayagüez Bay. The results were used to estimate TSS based on b_b and R_{rs} and then produce a three-dimensional TSS description along the bay. A significant relationship (r^2= 0.91, n=75) resulted between TSS and b_b675. Therefore, an algorithm was developed based on a linear equation: TSS=87.718*(b_b675) + 1.876. The validation also showed a significant relationship (r^2=0.85, n=12). Backscattering measurements of August 2005 (associated to a raining event), were used to estimate TSS and obtained a vertical profile of sampled stations. The first attempt to establish an algorithm to estimate TSS using R_{rs} data was also performed. Not significant relationship (r^2=0.35, n=136) was found when all cruises were included in the analysis. However, a better correlation (r^2=0.64, n=46) was found when only data of the second period (July 2005-October 2006) was included. These results must be better evaluated to develop a more robust algorithm that can be applied to MODIS Band 1 data to estimate TSS concentrations in Mayagüez Bay. More information can be found in the appended report of Vilmaliz Rodriguez.

Task (2) Evolution and tuning of algorithm for Chl retrieval in PR coastal waters

Remote Sensing Reflectance (R_{rs}) measured with the GER-1500 spectroradiometer from April 2001 to May 2007 in Mayaguez Bay was used to validate the OC3M MODIS algorithm for Chl estimation. The first step consisted in averaging the R_{rs} at the same wavelengths of the three bands used in the algorithm. They are: band 9 (438 – 448 nm), band 10 (483 – 493 nm), and band 12 (546 – 556 nm). Then, the averaged values were used to calculate the concentration of Chl using the algorithm. Finally, the estimated MODIS Chl was compared with the measured (field) Chl-a collected during the same day of the R_{rs} measurements. The analysis shows that in most cases the MODIS algorithm overestimate the Chl-a. It was also shown that the highest overestimation occurs in stations closed to rivers mouth, where high suspended sediments and CDOM are found. This work clearly demonstrated how the OC3 MODIS algorithm fails for the estimation of Chl-a in Mayaguez Bay, even when field R_{rs} data are used. This suggests that the NASA Chl product from MODIS images and provided by NASA will provide bad estimates for this region. The next step in this project will be to test this hypothesis.

Future Tasks (From the Milestones)

Partial work has been done in the development of GIS database for land-sea interactions in Mayaguez Bay. This task is listed for the second year but it has already started. All bio-optical data collected in Mayaguez Bay from April 2001 to May 2007 has been reprocessed and carefully check in order to assure the highest quality. The data have been exported to the ArcView format in order to prepare the databases. Synoptic maps of all parameters will be developed very soon and then compiled in the web-base environment ArcIMS. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay.

Estimation of suspended sediments using MODIS 250 m bands in Mayagüez Bay, Puerto Rico

Submitted by José F. Martínez Colón, Undergraduate student, UPRM-Department of Geology

Abstract:

Large 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. A study was conducted using the high spatial and temporal resolution of MODIS (Moderate Resolution Imaging Spectroradiometer) multi-spectral sensor onboard the Terra and Aqua satellite. The work tested the reliability of a model developed by Miller and McKee (2004) to measure suspended sediment concentrations using Band 1 (620 – 670 nm) in Mayagüez Bay, Puerto Rico. The tested algorithm gave a low average correlation value (R^2 = 0.0845). This study demonstrates that a site-specific algorithm is needed to better estimate suspended sediments this area using MODIS.

Introduction:

There are many disciplines in science that have the particular needs of field work. However, as we have seen throughout history, many advances in technology have been developed to facilitate such studies. For these reasons, it has become increasingly necessary to provide new methods and techniques in order to make assessments on different scientific scenarios as accurately as possible. The use of Remote Sensing systems is no exception. For instance, it is suggested that suspended sediments are responsible for changing the optical properties of water in coastal areas (Lugo, 2002), and their estimation with remote sensors are still under validation.

The current study focused on the suspended sediments of Mayagüez Bay, located in the west part of Puerto Rico between latitude 18° 10' N and 18° 16' N and longitude 67° 10' W and 67° 14' W (Figure 1). This area is highly influenced by several rivers (Yagüez, Añasco, and Guanajibo) and anthropogenic activities (Rivera, 2003). The suspended sediments throughout the bay produce changes in ocean color (González, 2005). They can also affect phytoplankton biomass (Gilbes and Yoshioka, 1996). Furthermore, it influences the growth rate of coral reef (Cuevas, 2004). These factors are enhanced by seasonal river discharge and land run-off (Gilbes et al., 2002).

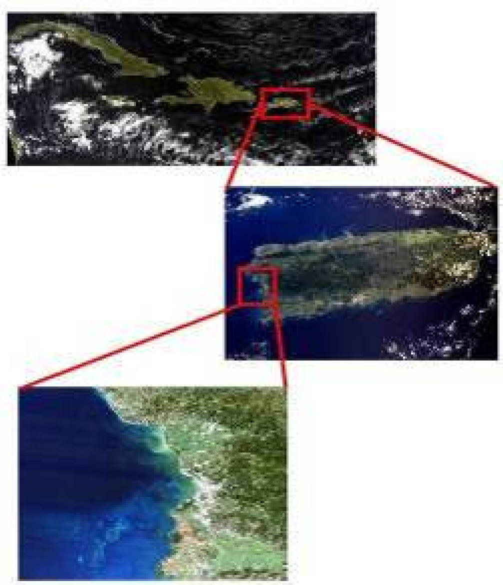


Figure 1: Location of study area: Mayagüez Bay, Puerto Rico
(images provided by the GERS Laboratory)

A previous undergraduate research was performed to estimate suspended sediments using remote sensing. González (2005) first studied the dynamics of river plumes around Mayagüez Bay using the AVIRIS (Airborne Visible/Infrared imagine Spectrometer) sensor (Figure 2). A new algorithm was also developed to estimate suspended sediments around Puerto Rico. In the same study a preliminary testing of MODIS (Moderate Resolution Imaging Spectroradiometer) imagery was done (Figure 3).

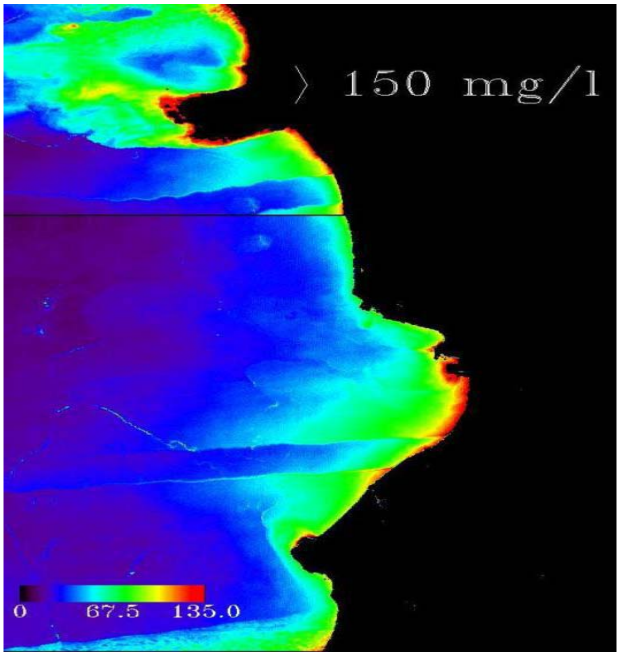


Figure 2: AVIRIS image of the west coast of Puerto Rico
(produced by González, 2005)

The spatial resolution of AVIRIS helped to provide good results. However, the tested 1 km resolution bands from MODIS proved to be limited. Her work showed that other approaches are needed to study suspended sediments in Mayagüez Bay.

Figure 3: Suspended sediment concentration as measured by MODIS around Puerto Rico
(produced by González, 2005)

According to Gilbes et al. (2002) it has become increasingly necessary to provide a new empirical algorithm to monitor and understand the dynamics of suspended sediment in Mayagüez Bay, using a more reliable spatial resolution. MODIS spectral bands 1 and 2 of 250 m resolution have proven to be useful in other coastal areas.

A previous work by Miller and McKee (2004) using that particular spatial resolution provided useful results of total suspended matter (TSM) in the coastal waters off the northern Gulf of Mexico. A linear relationship was established between band 1 (620 – 670 nm) of MODIS Terra and *in situ* measurements of TSM, providing evidence of the transport and fate of material in coastal environments (Figure 4).

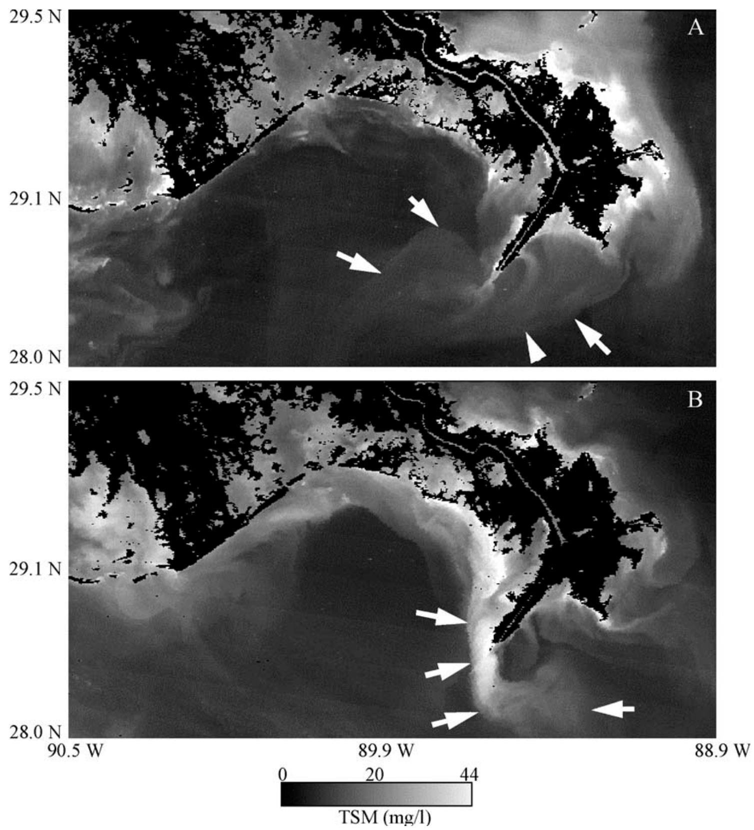


Figure 4: Calibrated images of TSM of the Mississippi River Delta and adjacent waters derived from MODIS Terra Band 1 (from Miller and McKee, 2004)

The project presented here followed Miller and McKee (2004) approach. The main purpose of this study was to validate their algorithm in Mayagüez Bay in order to evaluate the dynamics of suspended sediments. It was expected to have results with high degree of precision in respect to field samples and, in turn, provide a new study path to various other research questions.

Methods:

This project comprised three major phases. The first was data collection. *In situ* measurements of suspended sediments were obtained from field samplings at different stations in Mayagüez Bay (Figure 5 and Table 1). These were performed throughout several campaigns between 2001 and 2006.

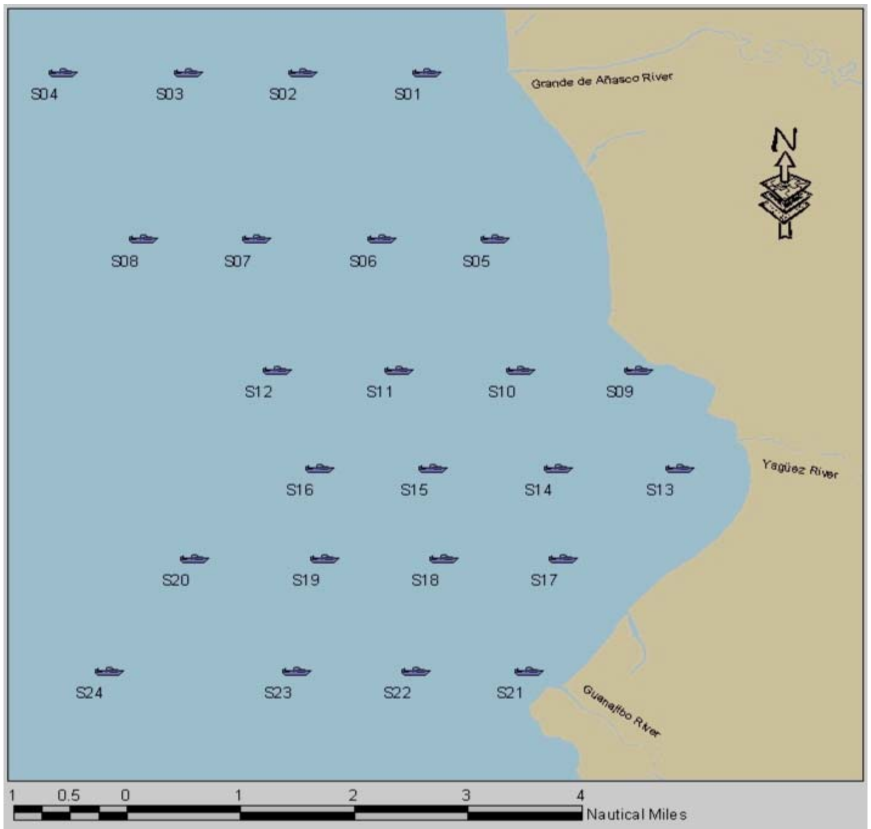


Figure 5: Location of sampling stations throughout Mayagüez Bay.

Table 1: Locations and dates of sampling stations

Station Number	Station Name	Latitude	Longitude
1	S1, A1*	18^{o} 16.00’	67^{o} 12.00’
4	S4, A2*	18^{o} 16.00’	67^{o} 15.20’
5	S5, AAA*	18^{o} 14.40’	67^{o} 11.40’
7	S7	18^{o} 14.40’	67^{o} 13.50’
9	S9	18^{o} 13.14’	67^{o} 10.14’
11	S11	18^{o} 13.14’	67^{o} 12.25’
13	S13, Y1*	18^{o} 12.20’	67^{o} 09.78’
15	S15	18^{o} 12.20’	67^{o} 11.95’
17	S17	18^{o} 11.33’	67^{o} 10.80’
19	S19	18^{o} 11.33’	67^{o} 12.90’
21	S21, G1*	18^{o} 10.25’	67^{o} 11.10’
23	S23	18^{o} 10.25’	67^{o} 13.15’
24	G2*	18^{o} 10.25’	67^{o} 14.80’

*** = samples in 2005 – 2006**

Afterwards, several MODIS images were obtained from NASA Archive Center for the same dates of field measurements. 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). For this study, particular consideration was given to band 1, which has a 250 m spatial resolution and a spectral range of 620-670 nm.

The second phase of this project was image preprocessing. The software used was ENVI 4.2 (Environment for Visualization of Images), available at the Computer Laboratory of the Department of Geology at UPRM. First, each image was fixed to the State Plane corresponding Puerto Rico (NAD 83). It was also necessary to create subsets to outline the area of interest. Then, the images were screened and chosen in terms of quality, taking into account cloud coverage over the study area and other image errors.
The selected images were corrected for the effect of the atmosphere. The procedure used was the Dark Pixel Subtraction method, which was also used by Miller and McKee
(2004). The darkest pixel in each image (lowest reflectance value) using band 2 was selected to fix the standard procedure already implemented in the software. The next step was to apply the following algorithm (as developed by Miller and McKee, 2004):

1140.25*(MODIS Band 1) – 1.91

This equation was applied to the images using the ENVI Band Math function. This way the raw digital values were converted to suspended sediment concentration values Figure 6 shows the relationship found by Miller and McKee (2004) in the Gulf of Mexico, which was used to develop the above algorithm.

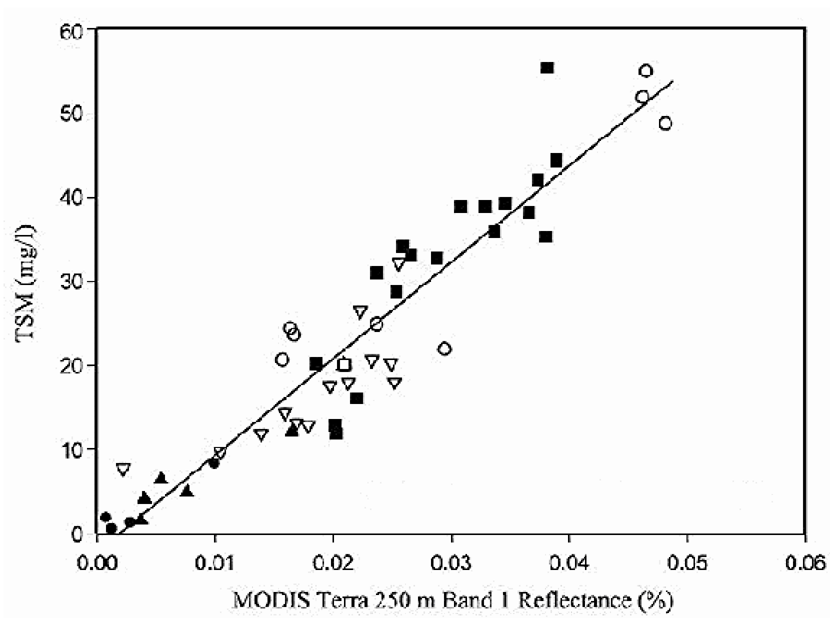


Figure 6: Total suspended matter as a function of atmospherically corrected MODIS Terra 250 m Band 1 reflectance (from Miller and McKee, 2004)

The third and final phase was to compare the MODIS estimates with the field
data. Each station had to be carefully located on the images using their exact coordinates, and then the values from the corresponding dates were compared. Afterwards, the results were plotted in a Field vs. MODIS data graph to create a regression line and analyze the results.

Results:

Comparisons between field measurements and MODIS data were difficult due to several concerns of image quality. Few stations were covered with clouds at the time of the field campaigns, therefore they were useless to provide accurate sediment concentrations. Also, some images had errors that made their processing impossible.

The suspended sediment concentration that was extracted from image reflectance was compared against the values taken from *in situ* measurements. The estimated values were very different in most stations, having only few that estimated the sediments accurately (Table 2). The concentration of suspended sediments estimated from the images was several times greater than the other measurements. A graph was developed using these results, having a very low correlation value (R^2) of 0.0845 (Figure 7). This shows that despite the MODIS Terra 250 m bands have good spatial resolution the relationship from the model was inconsistent throughout the studied area.

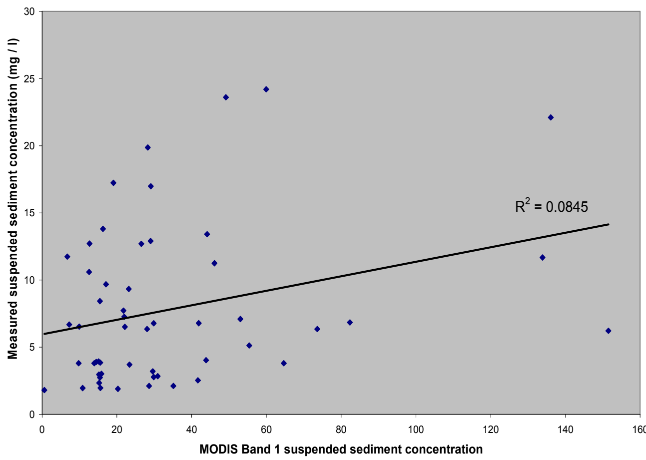


Figure 7: Relationship of Suspended sediment concentrations between field data and MODIS Terra 250 m Band 1 estimates.

Examples of the processed MODIS images are presented in Figure 8.

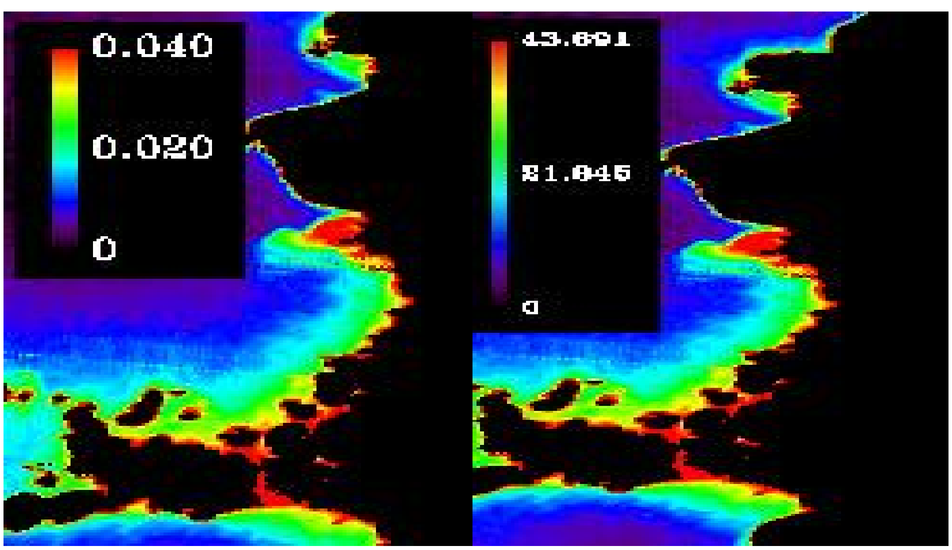


Figure 8: MODIS Terra 250 m Band 1 images from October 4, 2001 generated using ENVI 4.2 (Left: Image after atmosphere correction; Right: Image after application of algorithm)

Discussion:

MODIS imagery with a spatial resolution of 250 m should provide better results than 1 km imagery. However, this study has shown that its ability to measure suspended sediment over Mayagüez Bay still needs to be revised. The results obtained using the algorithm developed by Miller and McKee (2004) showed values that greatly surpassed the results from field measurements. This is well demonstrated by the low correlation value ($R^2 = 0.0845$). There are several reasons that could explain why this particular model was not appropriate for Mayaguez Bay. Based on the results, there are two main conclusions: the effects of the atmosphere and differences between coastal environments (discharge variations between Mayagüez Bay and Mississippi River delta).

The high temporal and spatial resolution that MODIS Terra provides at 250 m has proven to be a valuable tool for monitoring coastal and estuarine waters. However, no robust atmospheric correction method currently exists for these data. The method used by Miller and McKee (2004) of Dark Pixel Subtraction could be used for a wide variety of sky conditions, but it is still vulnerable to noise ratio effects (Shutler et al., 2007). Even more so, the pixels that get mixed with cloud coverage signals influence greatly the estimation of properties, such as suspended sediment concentration.

The other possible reason that makes the model inappropriate is the differences between the northern Gulf of Mexico and Mayagüez Bay coastal environments. The main variation is river discharge. The rivers that influence the coastal waters of Mayagüez Bay are Yagüez, Guanajibo, and Añasco, where this last is the principal sediment supplier (González, 2005). According to USGS annual statistics for the project's time frame, the discharge from this particular fluvial system ranges from 290.8 f^3/s to 551.9 f^3/s (Table 3). On the other hand, the discharge estimates for the Mississippi River system, range from 200,000 f^3/s and 500,000 f^3/s (Coupe and Goolsby, 1999). This suggest that the sediment load carried by the river systems in Mayagüez Bay is much lower than in the northern Gulf of Mexico. Also, the amounts of re-suspended sediments are very different.

Table 3: Añasco River annual discharge
(from US Geological Survey, 2007)

Water Year	Discharge (f^3/s)
2001	290.8
2002	404.6
2003	304.1
2004	551.9

Further investigation is needed to develop an accurate algorithm to estimate suspended sediment concentration over Mayagüez Bay. It is important to take into account the variables explained before in order to adjust it to better estimate the concentrations measured in the field and make it suitable to the conditions of the studied area. As suggested by Miller and McKee (2004), the use of MODIS Terra 250 m Band 1 can provide good results, since 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. It is also important that the atmosphere be corrected using the Dark Pixel Subtraction method, it keeps consistency and simplicity.

Conclusion:

The use of remote sensing techniques promises to be an excellent tool to estimate suspended sediment concentrations. The spatial and spectral resolution of MODIS Terra 250 m Bands shows that images can be generated with good quality standards. However, the application of this sensor in Mayagüez Bay needs further analyses and understanding of certain variables that may affect the results. The atmospheric conditions and amount of river discharge have a direct effect in the tested algorithm. In order to achieve accurate estimates it is necessary to develop a site-specific algorithm that fits the conditions of this area. It is expected that the development of a more reliable algorithm for the Bay could hold the key for many more research opportunities.

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Dynamics of Chromophoric Dissolved Organic Matter (CDOM) in Coastal Tropical Waters

Submitted by Patrick Reyes Pesaresi, Ph.D. Candidate, UPRM-Department of Marine Sciences

Field work May 1-2 2007 cruise:

During this work period a cruise comprising two days was scheduled for the month of May. During the first day a total of 8 stations were performed but only two stations were successfully recorded on the data logger. During the second day the instrument of the bio-optical package were mounted in a flow trough mode by means of a pump. The parameters (absorption and attenuation coefficient, salinity, chlorophyll-a fluorescence, and photosynthetic efficiency) were continuously monitored at one-meter depth. In the meantime water sample were collected for TSS, CDOM and Chl-a concentration determination on the 8 pre-establish stations and between each station after the water passed through the instruments. Simultaneously GPS positioning was also recorded during the cruise, hopefully the gathered data will be used to generate a map for all the recorded parameters using ArcGIS program. Water samples (CDOM, Chl-a, TSS, and GPS position) were collected in the estuarine area of the Añasco, Yagüez, and Guanajibo Rivers at three different points with a kayak. All the water samples have been finally analyzed, and the data used to update our correlation analysis.

Precipitation and River Discharge data:

The rain gauges lactated in the watershed of the Añasco, Yagüez and Guanajibo Rivers were identified and the data was downloaded for the study period (2004-2007) forms the National Weather Service COOP Stations from their web page. A total of 9 precipitation monitoring stations were selected for the study area and the data gather for the study period from January 1, 2004-June 30, 2007.

COOP ID		COORDINATES	
	Station Name	Lat	Lon
660061	ADJUNTAS SUBSTATION	18.17	-66.8
664330	HACIENDA CONSTANZA	18.22	-67.08
664677	INDIERA ALTA	18.17	-66.88
665908	MARICAO 2 SSW	18.15	-66.99
665911	MARICAO FISH HATCHERY	18.17	-66.99
666083	MAYAGUEZ AIRPORT	18.25	-67.15
666073	MAYAGUEZ CITY	18.19	-67.14
668536	SABANA GRANDE 2 ENE	18.08	-66.93

Data for River Discharge was downloaded from the USGS database for the Añasco and Guanajibo River only since no monitoring station is located in the Yagüez River. The monitoring station used were the Guanajibo Station located at Hormigueros (USGS # 50138000) and the Añasco River station located at San Sebastian (USGS # 5014400). In our case the River discharge was expressed in cf/s and the data was converted to m^3/s per day. For our analysis the discharge for the 3 previous days before and the same cruise day were average and this value used for our correlations.

Ac-9 data Correction and profile generation:

For this summer period all the Ac-9 generated data have been arranged by cruise in an excel worksheet that makes all the necessary data correction for: in *situ* salinity and temperature, scattering, and water blank. This generated data can then be used to generate profiles for each of the 9 absorption and attenuation channel. In our case only the 412 nm absorption and attenuation channels for total CDOM have been used to generate profile (Figure 3-8). For the CDOM generated profiles during the rainy season months it is possible to observe a higher total CDOM absorption coefficient during that period that is also related to a lower salinity in the same station indicating a terrestrially derive CDOM signal (Figure 4-8 CDOM). It is observed that during the dry season a homogeneous high salinity water column is observed that coincides with the lower homogeneous CDOM absorption coefficient profile (Figure 8).

CTD Generated profiles:

Salinity profiles were generated for each station from 2004-2006. For the inshore stations it is possible to observed that during the rainy season month (August and October 2005) a low salinity lenses can be found in the inshore stations (A1 and G1), and these can also be observed even for the month of October 2005 even for offshore station A2 (Figure 5).

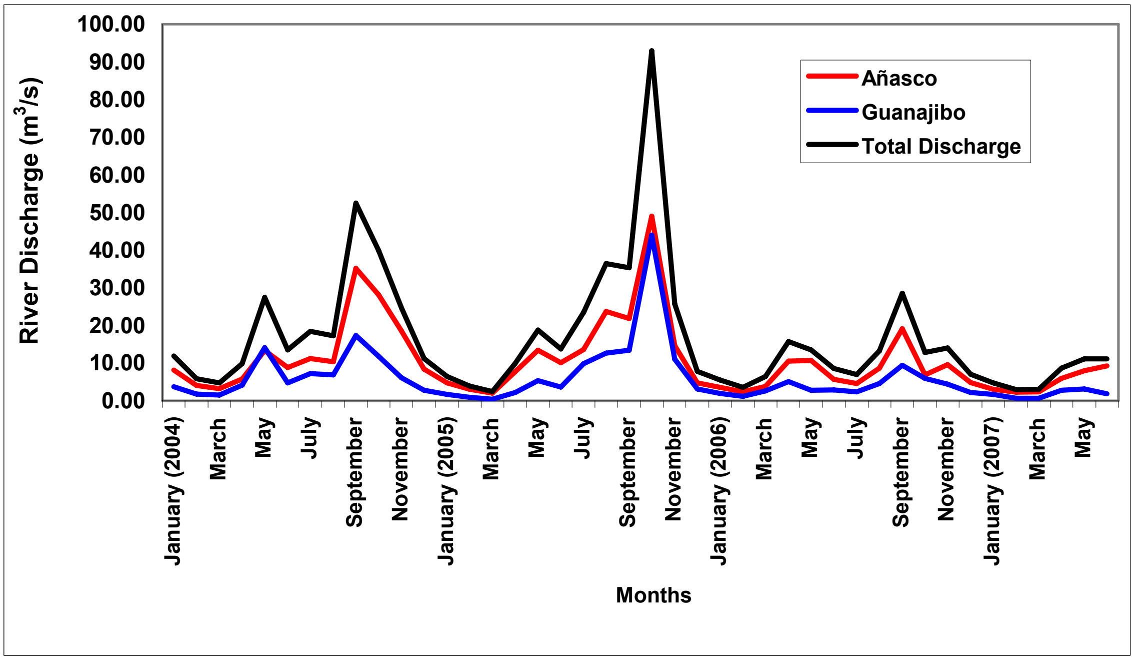
River Discharge correlation analysis:

During the correlation analysis between River Discharge and all the others measured parameters, relatively good correlation were found for the Guanajibo inshore station G1 (Figures 9–12). After comparing these correlations with the Añasco River inshore station A1 it was observed that the R^2 were very low compared with R^2 for the G1 stations. These could differences could be due for several factors: First, the River discharge data for the G1 Station is monitored very close to the estuarine in the case of the Guanajibo river and very few tributary drain to the river after the monitoring station. This makes the river discharge data a good approximation of the actual discharge at the river mouth. Second, the monitoring stations at the Añasco River is located well up river in the San Sebastian area, very far from the actual river mouth. Other smaller creeks drain to the main river after this station (Grove, personal communication) making the river discharge data provided by the USGS un-reliable measurement that cannot be extrapolated as a real discharge at the estuarine area. Third the G1 station is located closer to the shore than the A1 station making the river influence on the inshore stations more evident (lower salinity) during a heavy rain event. We suggest that a model should be used to estimate the actual Añasco River discharge at the river mouth since the river discharge is well underestimated making this fact a problem at the time to make correlations difficult due to the great error involved in the discharge estimates.

Remote Sensing Reflectance:

Remote sensing reflectance data gathered for all our cruises since 2001-2007 was organized in only one Excel page for all our 19 cruises and having a total of approximately 130 remote sensing reflectance curves. This makes the retrieval of this data easer to accesses and used for the further development of algorithms that can be used to estimate different components found in the water column.

Figure 1: River Discharge for the Añasco River at San Sebastian Station and Guanajibo Rivers at Hormigueros Station for January 1, 2004 to June 30, 2007*.



Data from the U.S. Geological Survey water data report stream water flow.

Figure 2: Total river discharge and salinity for inshore and offshore stations in the surface and depth during the cruise.

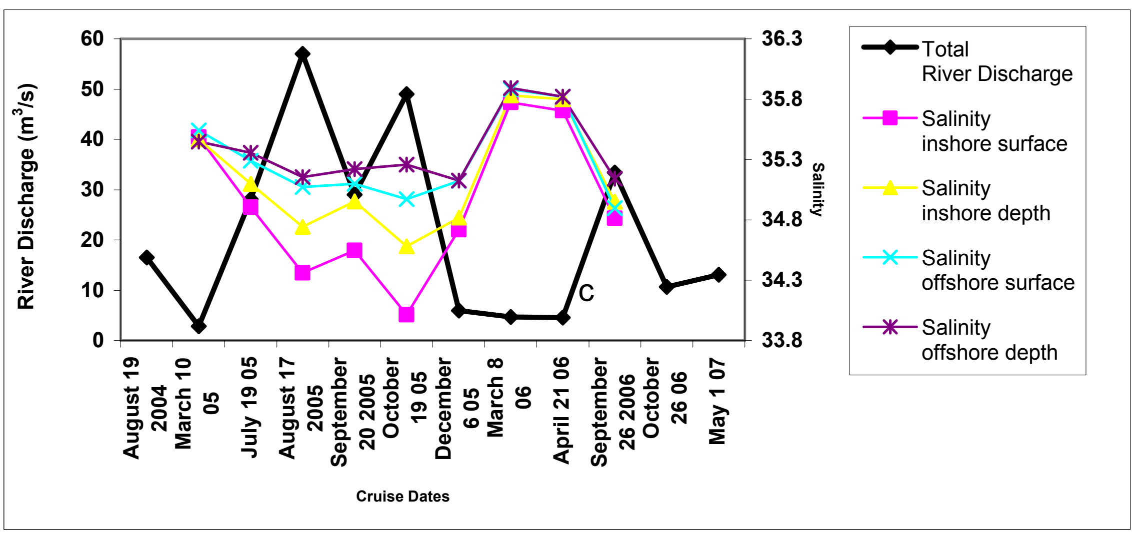


Figure 3: Salinity profile for the A1 station (inshore) for all the cruises from 2004-2007.

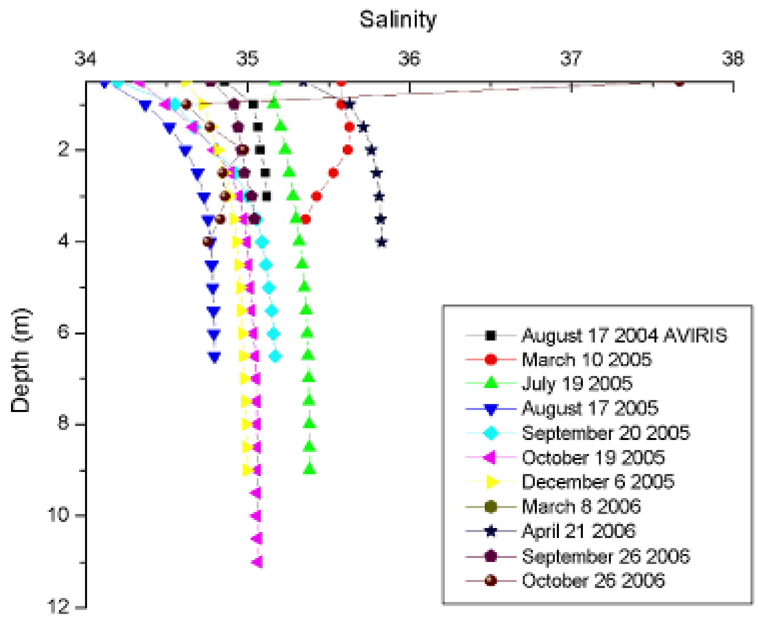


Figure 4: CDOM absorption coefficient profile for the A1 station (inshore) for all the cruises from 2004-2007.

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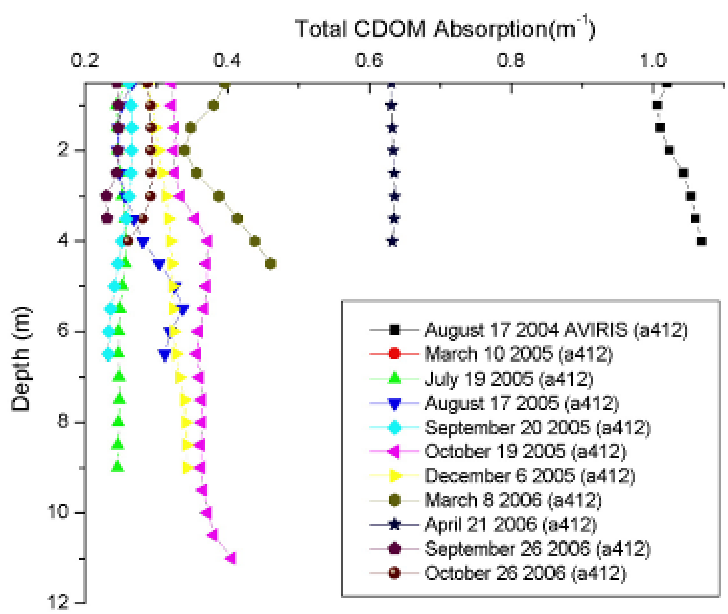


Figure 5: Salinity profile for the A2 station (offshore) for all the cruises from 2004-2007.

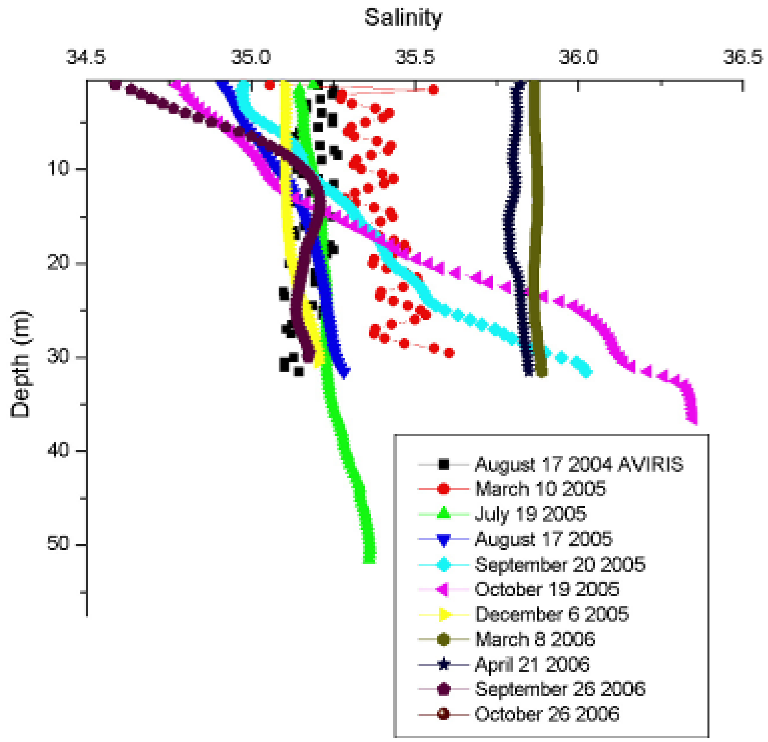


Figure 6: CDOM absorption coefficient profile for the A2 station (offshore) for all the cruises from 2004-2007.

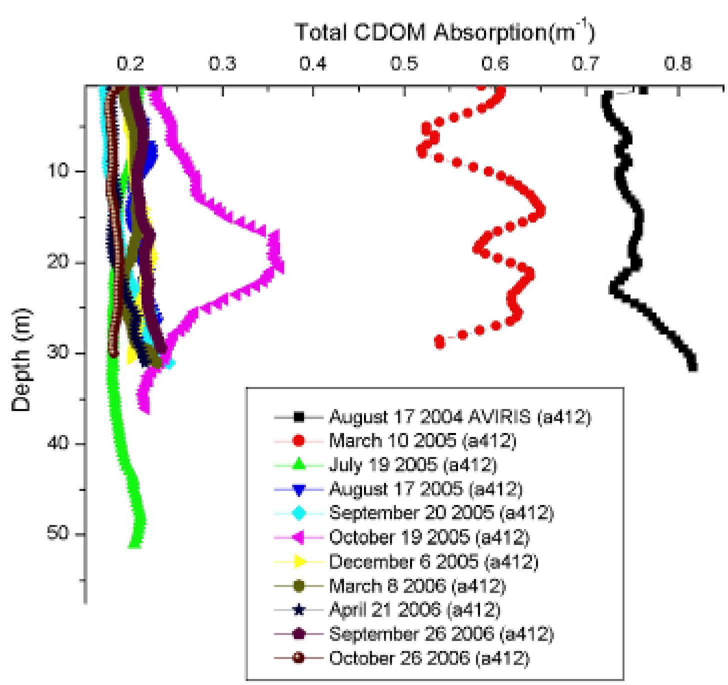


Figure 7: Station salinity profile for the G1 station for all the cruises from 2004-2007.

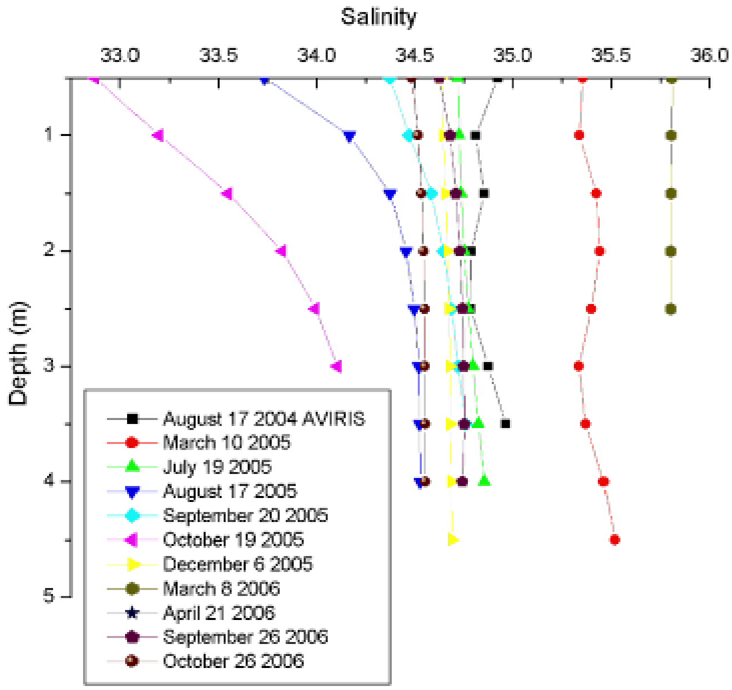


Figure 8: CDOM absorption coefficient profile for the G1 station for all the cruises from 2004-2007.

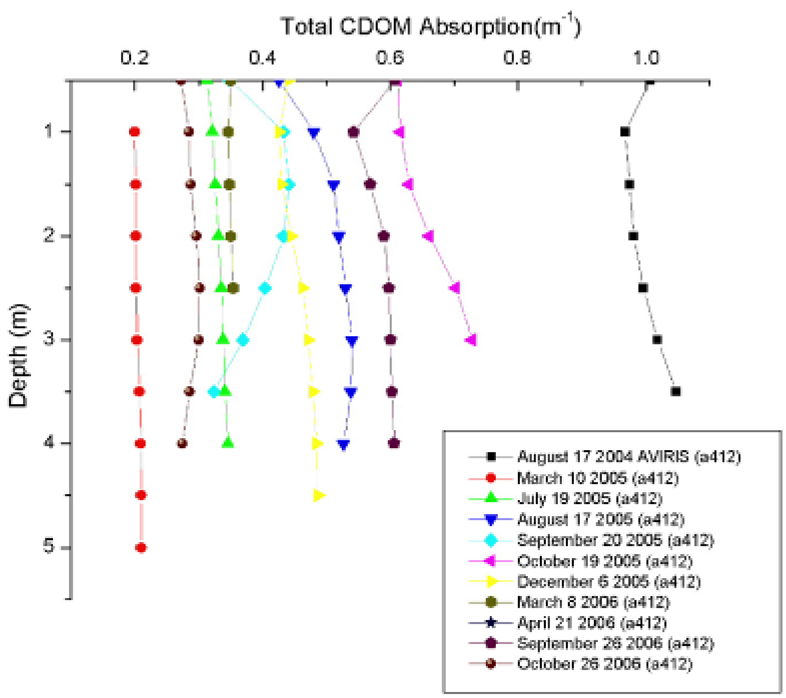
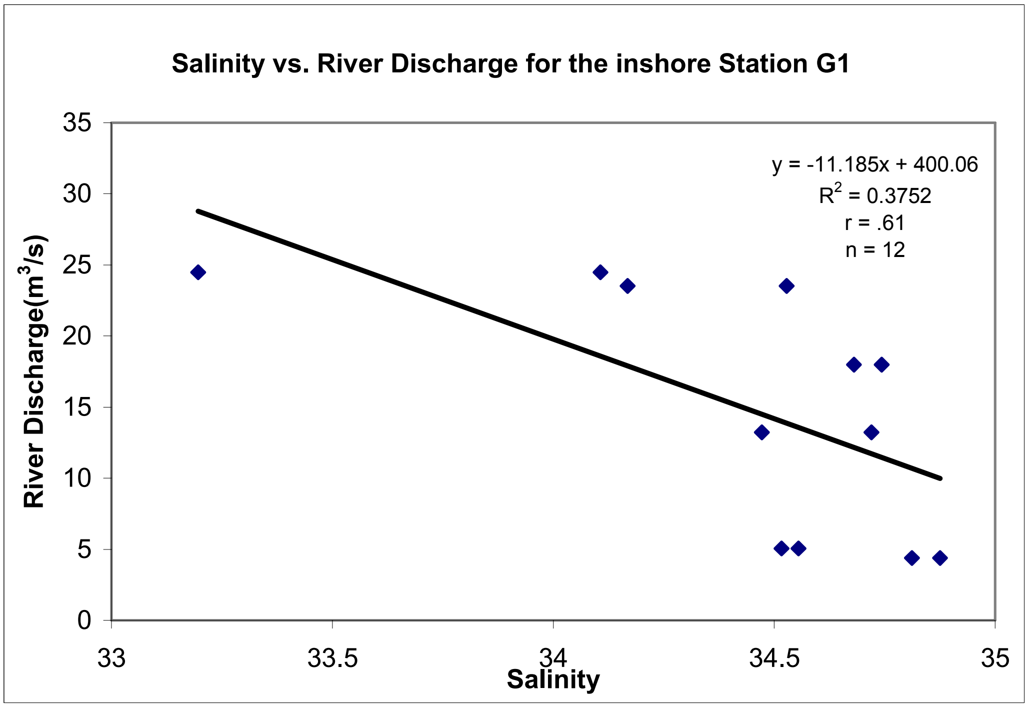


Figure 9: Comparison between the Correlations for the Salinity vs. River Discharge for the inshore G1 and A1.



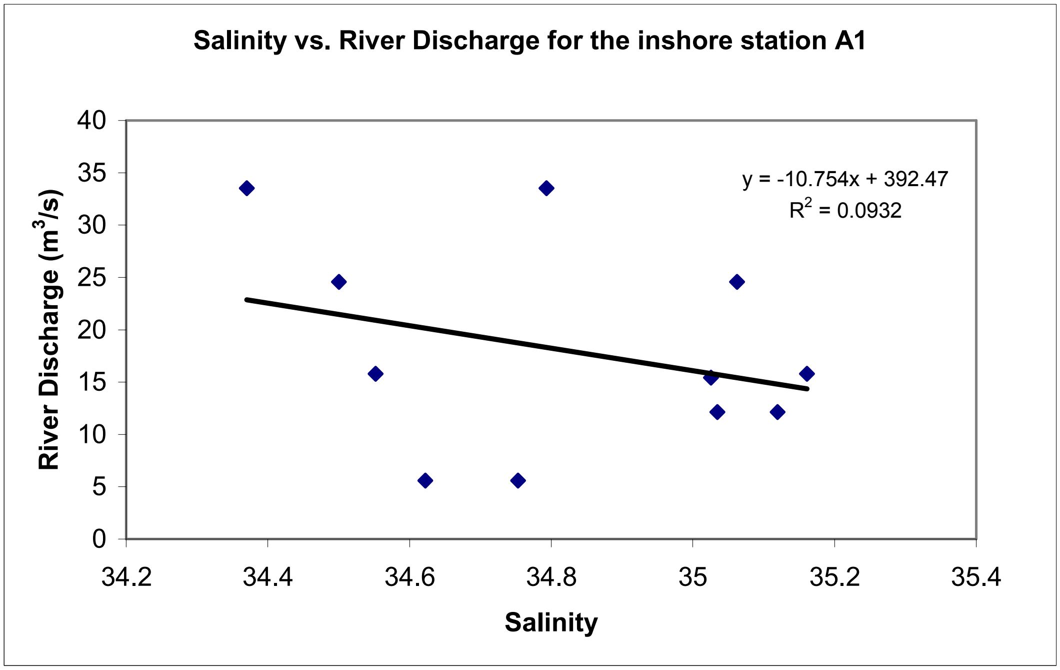
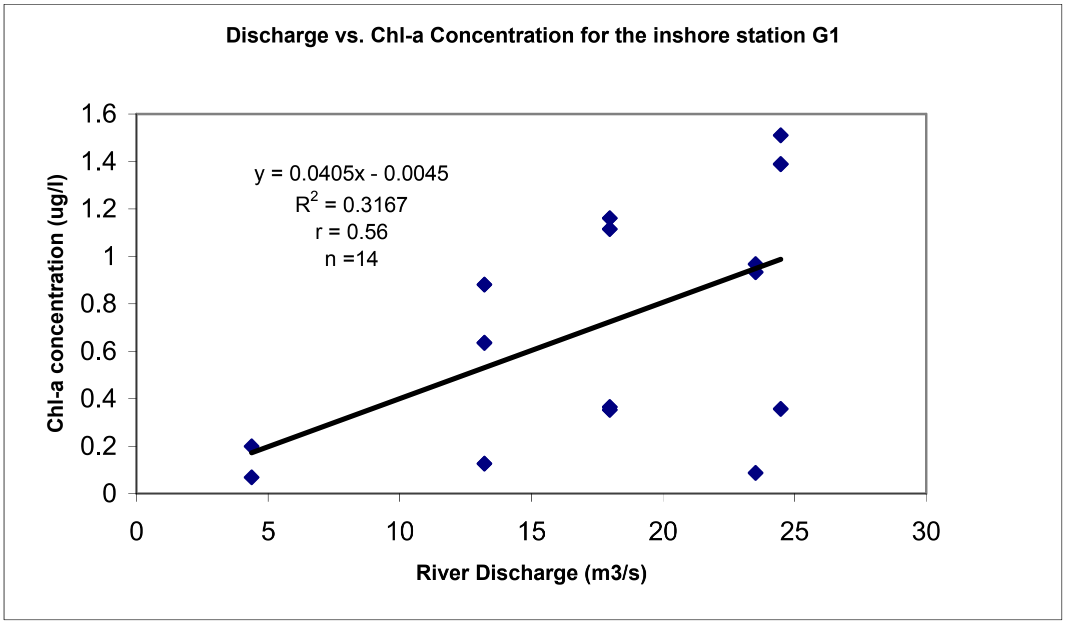


Figure 10: Comparison between correlations for River Discharge vs. Chl-a for the inshore G1 and A1.



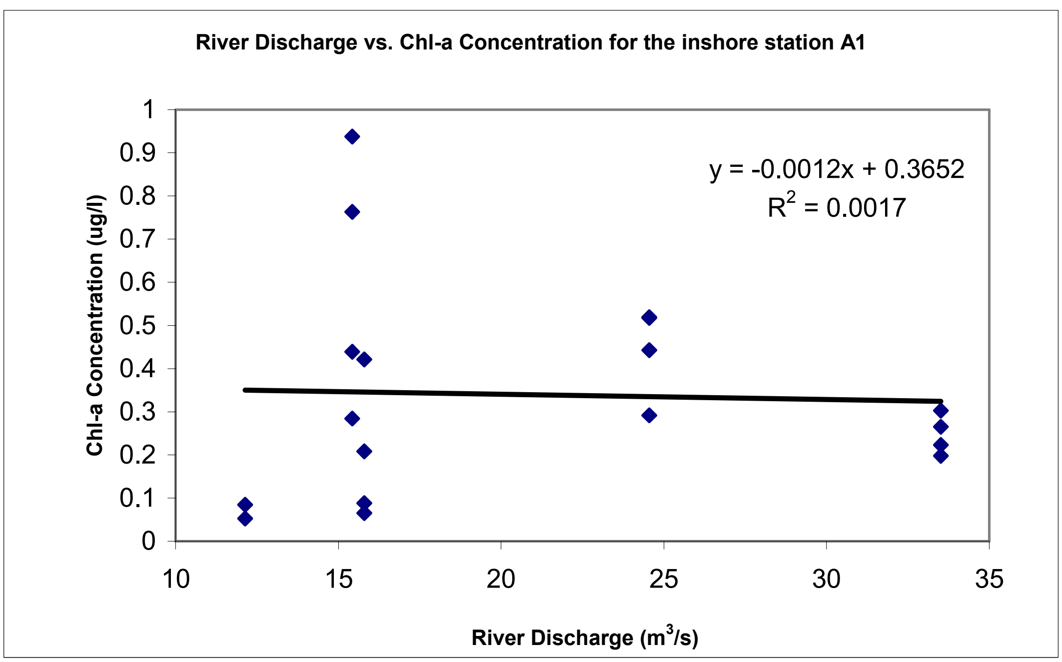
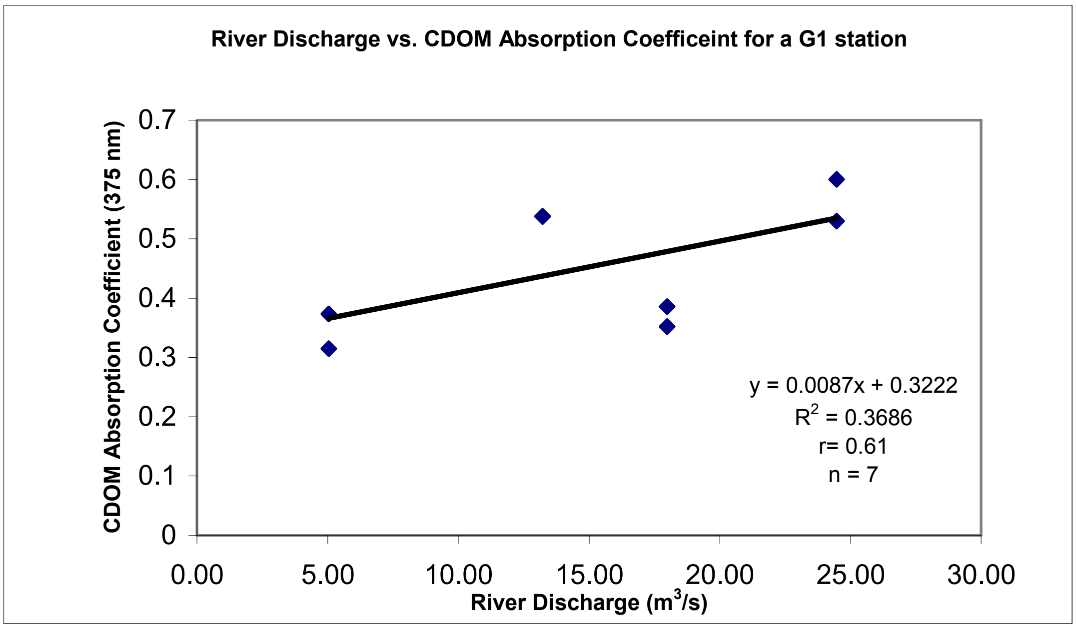


Figure 11: Comparison between correlations for River Discharge vs. CDOM absorption coefficient (375 nm) for the inshore G1 and A1.



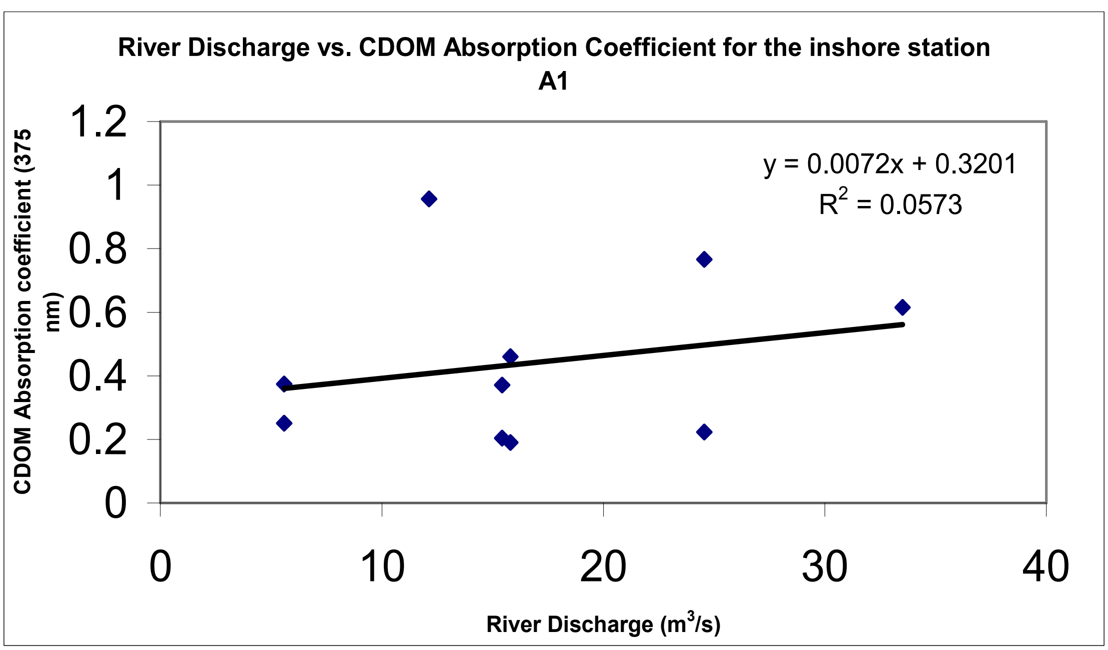
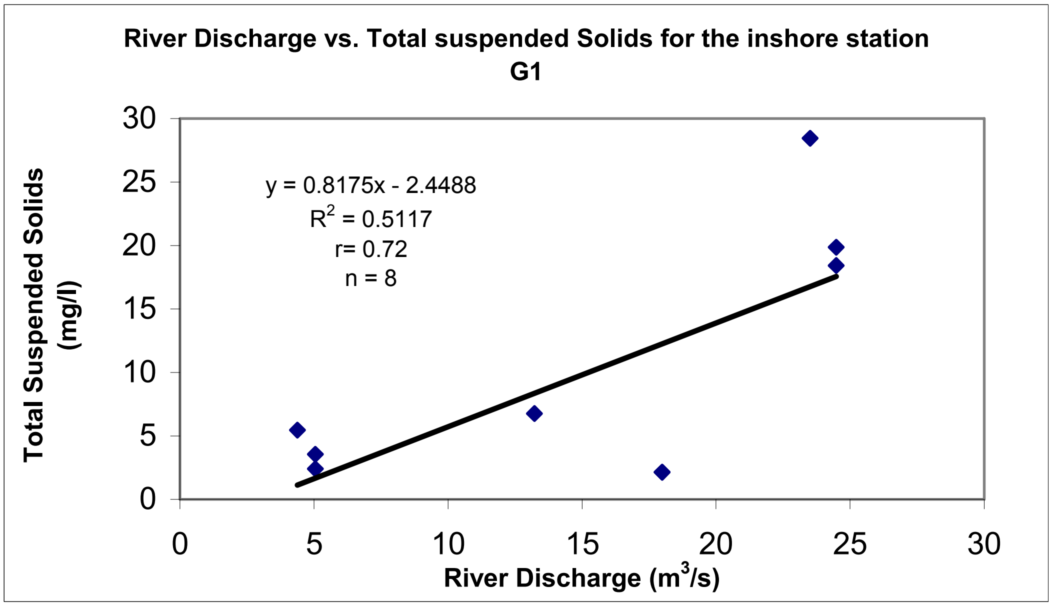
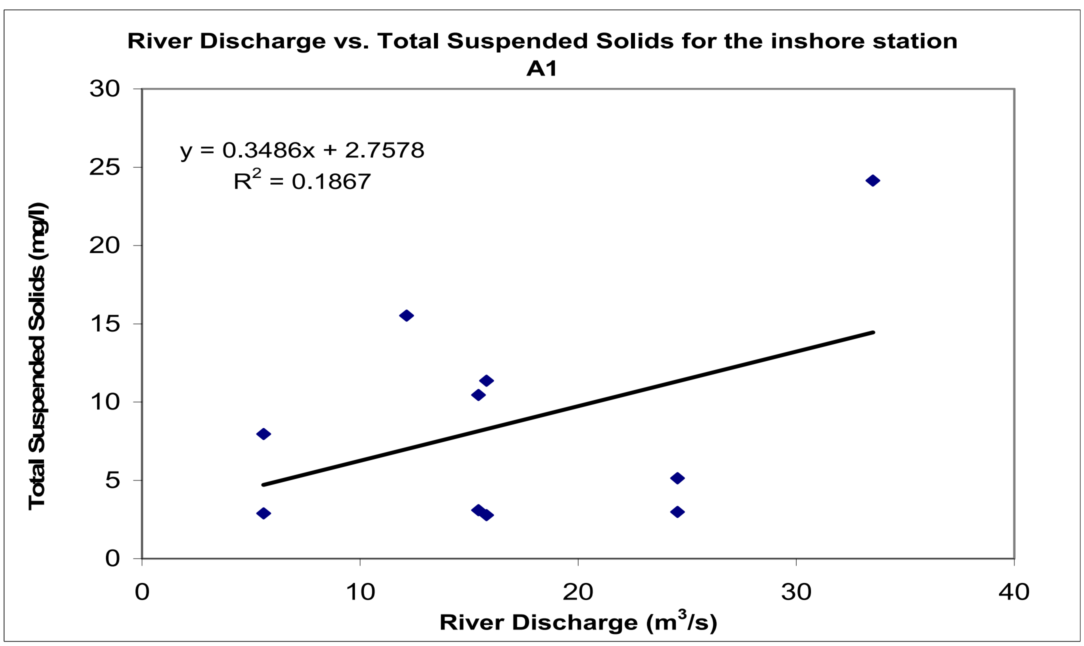


Figure 12: Comparison between correlations for River Discharge vs. TSS for the inshore G1 and A1.





Relationship between the backscattering coefficient, remote sensing reflectance, and the suspended sediments in Mayagüez Bay

Submitted by Vilmaliz Rodriguez, Master student, UPRM-Department of Geology

Introduction

Optical properties of water represent an excellent attribute to indirectly estimate important water parameters, such as total suspended solids (TSS), CDOM and chlorophyll-*a* fluorescence. This provided an exceptional resource to better describe the distribution of these parameters without direct measurement, a process that is generally extremely labor intensive. Scattering is a fundamental process in light propagation in the ocean, where electromagnetic radiation is deflected from its original beam by particles. The backscattering coefficient (b_b) indicates, in units of m^{-1}, the attenuation caused by scattering at angles from 90° to 180°. A good analysis of ocean satellite images and other reflectance information required understanding of this parameter; for example, in ocean waters satellite sensors essentially recorded images of backscattered light (Dana et al., 2002).

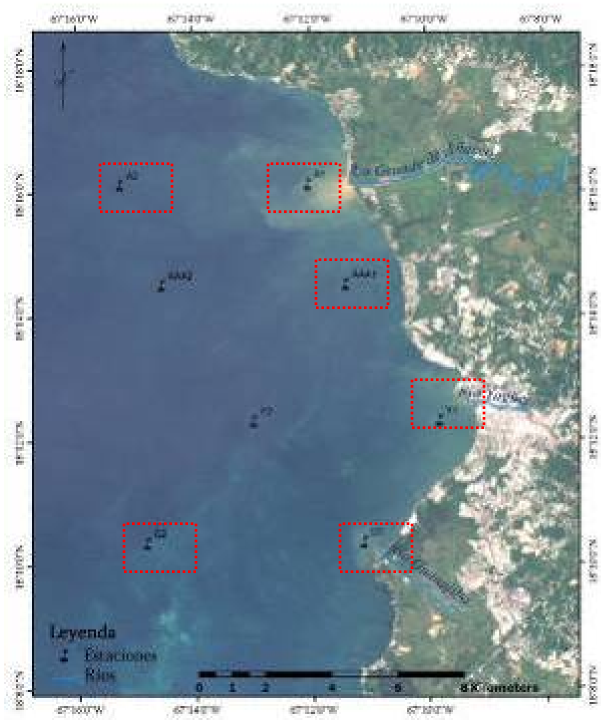


Figure 1. Eight stations monitored for bio-optical properties. In six of these station water samples are collected for TSS concentration and other laboratory measurements (red dots).

Solid suspended concentrations in coastal waters are influenced by sediment transport, deposition, and suspension processes. Understanding the occurrence and behavior of all these processes is crucial to reach the final general objective of this study, which is to describe spatial variations of TSS along the Bay associated to landward erosion. For instance, sedimentation processes in the southern area of Mayagüez Bay are dominated by re-suspension events (Morelock et al., 1983), and not by river discharged (Guanajibo River) as expected, therefore, knowledge of this process patterns is needed to establish a land-sea interface.

This part of the study is attempting to establish a relationship between b_b, remote sensing reflectance (R_{rs}) and TSS using *in situ* measurements in Mayagüez Bay. The results obtained will be used to estimate TSS based on b_b and R_{rs} to then produce a three-dimensional TSS description along the bay. This description will be also used for satellite images interpretation and algorithms evaluation.

METHODOLOGY

The Mayagüez Bay has been monitored for optical properties and other water quality parameters in 19 research cruises since April 2001. The number of stations visited during the cruises has varied from 24 to 8 stations. For this part of the study the data used is from those stations where water samples were collected for TSS measurements (Fig.1).

Figure 2: Bio-optical package with instruments identified

A HydroScat-6, instrument part the rosette bio-optical package (Fig 2), measures backscattering at six different wavelengths (442, 470, 510, 579, 620 & 671/675 nm). This instrument estimates b_b from measurements of the Volume Scattering Function (VSF) around a single fixed angle of 140º. However, is not easy to obtain reliable data of this coefficient because it is generally difficult to measure. A quality control process was applied to the data set to identify the best data for the analysis. The backscattering values obtained in stations A1 and G2 were plotted versus wavelength producing two different curves for each cruise. These two stations were selected since A1 usually presents characteristics of waters with high turbidity, while G2 represents clear waters. The curves were identified as typical when they showed similar spectral shapes to those published on Morel (2007), and atypical when prominent peaks were observed in any of the wavelengths (Fig. 3).

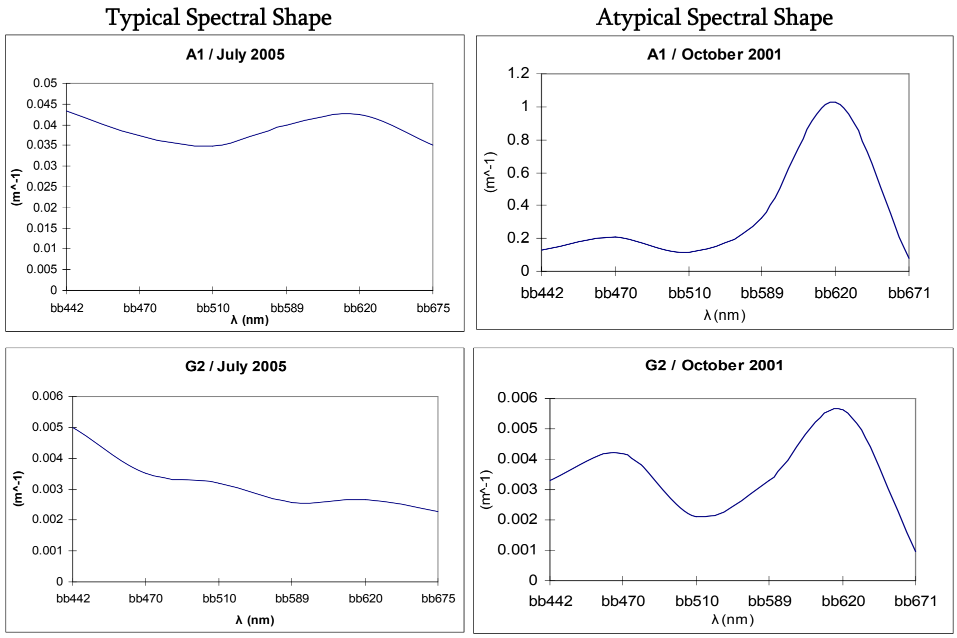


Figure 3. Examples of typical and atypical curves obtained during the quality control process. *These curves are presented as continuous lines for visualization purposes, but measured values are only present in the six wavelength included the x axis.*

After this process, it was decided that the best b_b data included all the measurements collected since July 2005 to October 2006 (9 cruises). Before this date the instrument was repaired and calibrated, therefore the measurements of this period are expected to be more reliable for the analysis. Eighth of nine data-sets were used to establish the relationship between b_b in six different wavelengths and TSS, first including all the TSS data, and then separating it as deep and surface measurements. Four outline values were eliminated from the analysis considering an apparent mal function of the instrument (HydroScat-6). The data collected in the cruise that took place in October 2006 was not included in the analysis to use it for validation. Estimations of TSS were made based on the regression equation obtained when all the data was included.

The first attempt in the process of developing an algorithm to relate remote sensing reflectance and TSS is also presented in this report. The final resultant algorithm will be applied in the estimation of TSS using MODIS Terra band 1 data (250m, 620-670 nm). A spectoradiometer (GER 1500) was used to obtain the R_{rs} values in all the stations. For each station, a mean value was calculated of the reflectance values obtained within the range of 620 and 670 nm (Band 1, MODIS). In this first attempt, all the reflectance values calculated were plot vs. TSS measurements obtained at surface level.

RESULTS AND DISCUSSION

A significant relationship (r^2= 0.91, n=75) resulted between TSS concentration (mg/l) and b_b at 675 nm (Fig. 4a). Good relationships were also observed in all the other five wavelengths measured by the HydroScat-6 (Fig. 4b-f). The high relationship obtained with the 675 nm wavelength showed that a large amount of the backscattering occurring in these waters is produced by orange to reddish particles, as clays. When the regression was separated in deep and surface measurements both cases presented also best correlations on 675 nm, however the relationship increased with deeper measurements and slightly decreased with surface data (Fig. 5). An explanation to this observation is that variations in TSS concentration are higher at the surface level, therefore water samples collected (TSS) in this zone might not be representative of the backscattering at the depth selected. On the other hand, in deepest areas the TSS concentrations are more homogeneous decreasing the sample collection effect to the association of these two parameters.

It was determined that the best equation to estimate TSS based on b_b was the one obtained using all the data and the 675 nm wavelength (y=87.718x + 1.876). The validation process showed a significant (r^2=0.85, n=12) relationship between measured and estimated TSS concentration (Fig. 6).

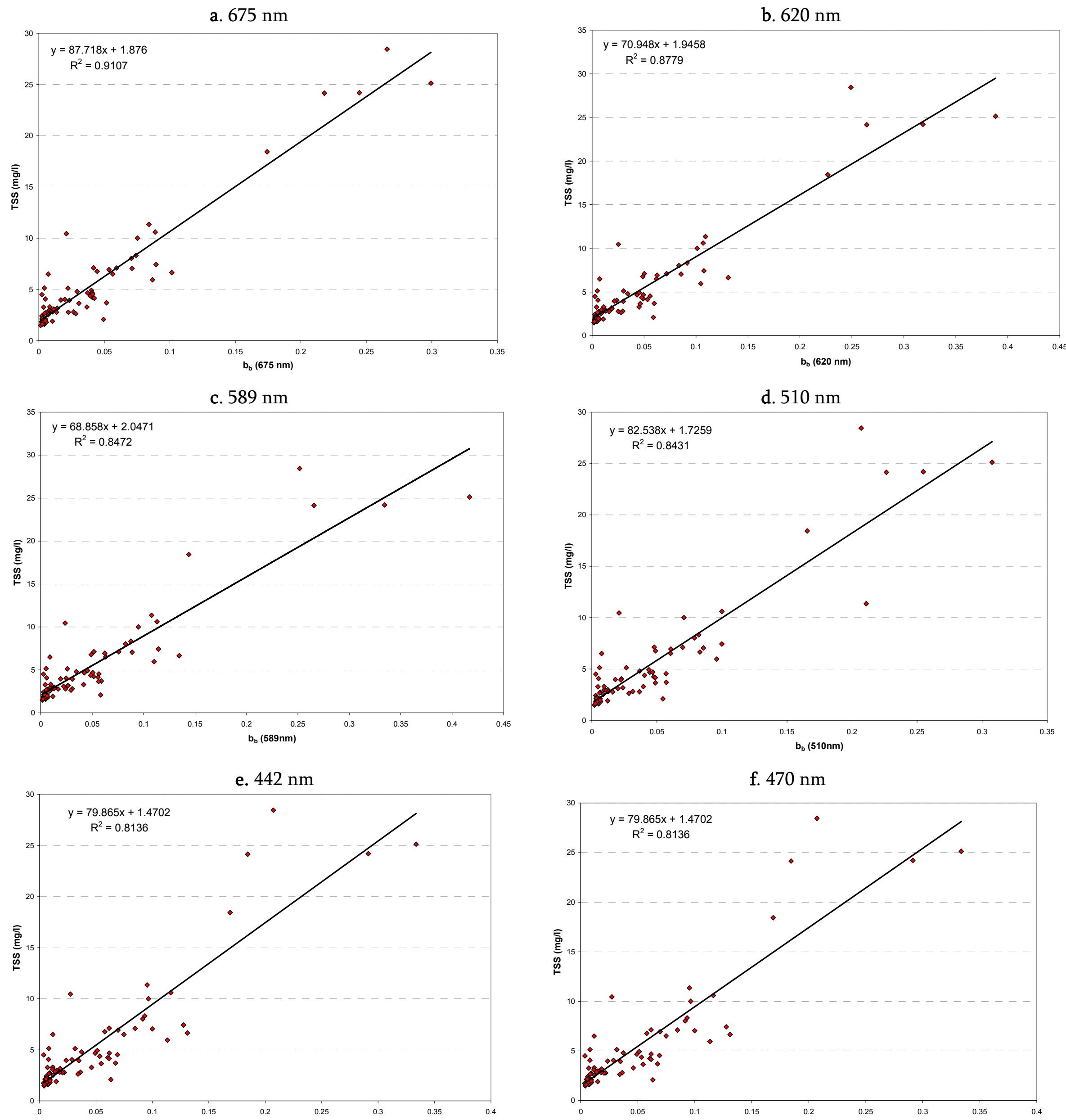


Figure 4a. Relationship between TSS (mg/l) and b_b at six different wavelengths

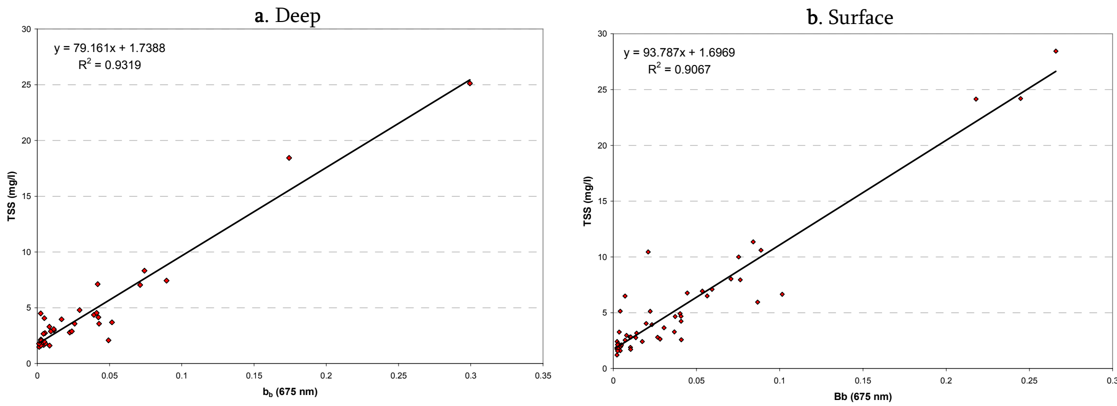


Figure 5. Relationship between TSS (mg/l) and b_b using depth (a) and surface (b) measurements

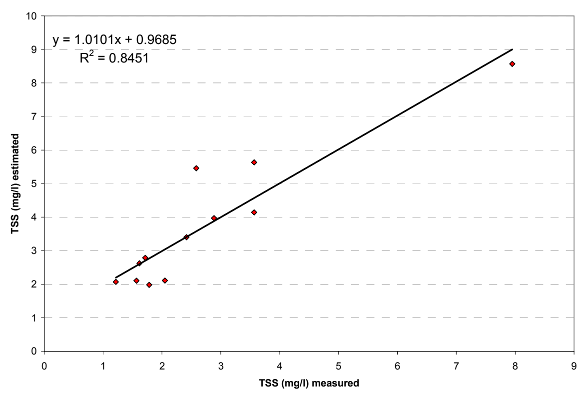


Figure 6. Validation of algorithm developed to estimate TSS based on b_b using October 2006 cruise data

In general, the algorithm produced is expected to give a good quality estimation of TSS concentration in a vertical profile for all the cruises developed since July 2005.

Backscattering measurements of August 2005, which are associated to a raining event (USGS discharge data), were used to estimate TSS an obtained a vertical profile of all eight stations monitored (Fig.1). The values obtained were plotted first, including all the stations (Fig 7a.) and the separating them between coastal and oceanic stations (Fig. 7b & c). The coastal stations showed higher TSS concentrations and significant variations within the profile. The AAA1 presents similar values and behavior than the oceanic stations since this area is not directly affected by rivers as occurring in the other three coastal stations. The influence river discharged can be better detected in A1, where the concentration of TSS decreased dramatically from 0.5 to 1 meter showing that the material discharged by the Añasco River is mainly staying as a thin layer in the upper part of water column. TSS concentration is also higher at surface in Y1 station, but the layer in this case is thicker (~2 m) than in A1. On the other hand, higher amount of TSS in G1 are concentrated in the deepest regions suggesting that suspended material in this area is influenced by re-suspension more than river discharged. When the oceanic values are plotted individually, variations can be observed in A2 and Y2 through the water column. These variations are similar to those observed in the coastal area, but with lower concentrations. The thin layer with higher values observed in A1 is also present in station A2, and the abundance of TSS in Y2 is concentrated in the first 3 meters similar to estimated in station Y1. Once again, river discharged influence is

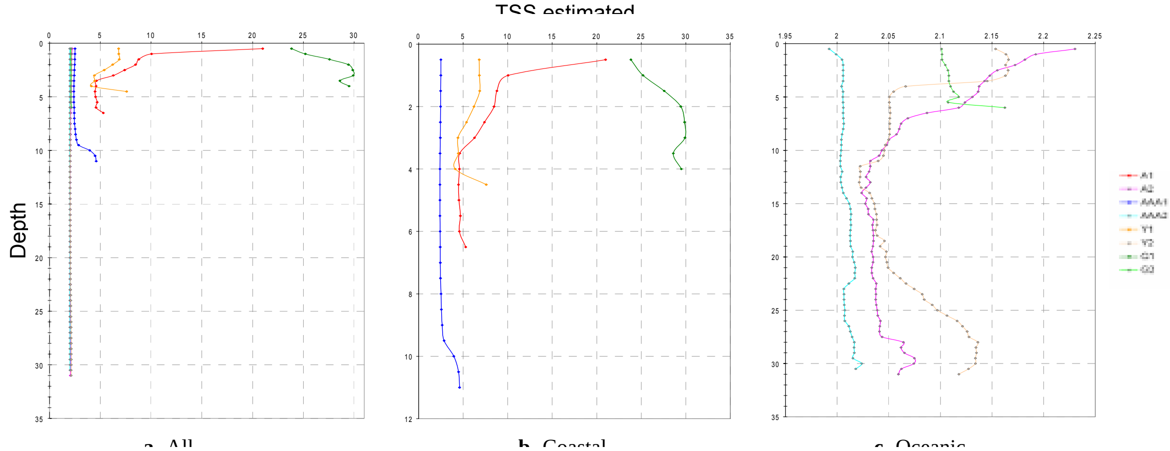


Figure 7. Vertical profile of TSS concentration (mg/l) estimated from b_b data corresponding to eight stations distributed along the Mayagüez bay.

not of detected in G2, and re-suspension is also affecting this area because values are generally increasing with depth.

The results obtained suggest that the method presented provide reasonable estimations that can be used to better describe the spatial distribution of TSS within the Mayagüez Bay under different conditions.

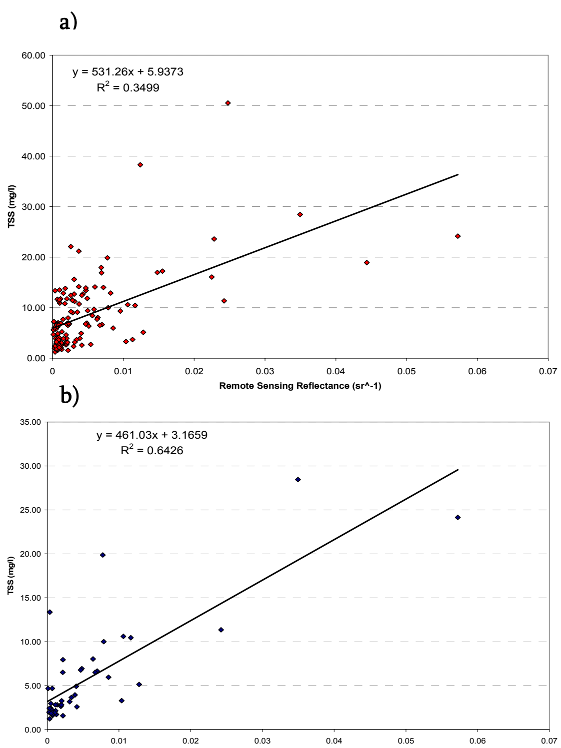


Figure 8. Relationship between Remote Sensing Reflectance and TSS concentration (mg/l) at surface. a) Including all data collected since April 2001. b) Including only data obtained since July 2001 to October 2006.

The first attempt to establish an algorithm to estimate TSS concentration (mg/l) using remote sensing reflectance data was developed. Not significant relationship (r^2=0.35, n=136) was found when all cruises data was included in the analysis (Fig. 8a). These results were obtained using TSS measured at surface level, it is expected that the spectoradiometer is mainly measuring radiance at this level when waters presented high turbidity. Based on this principle it was considered that station G2 might be affecting the correlation because this station is dominated by clear waters and the area is relatively shallow, therefore the reflectance calculated for this station could be a result of the bottom and not the material suspended in the water column. However, the regression results did not changed (r^2=0.35, n=120) when this station was eliminated from the analysis.

A better correlation (r^2=0.64, n=46) was observed when only the data of the second period (July 2005-October 2006) was included (Fig. 8b). Possible differences between the first and the second period that might be affecting the data quality still need to be defined. The results obtained in this first attempt needed to be evaluated to establish a final algorithm that can be applied on MODIS Terra band 1 data to estimate TSS concentrations in Mayagüez Bay.

References

Dana, D.R. & Maffione, R.A. 2002. Determining the Backward Scattering Coefficient with Fixed-Angle Backscattering Sensors—Revisited. Presented as a poster at Ocean Optics XVI. HOBI LAB

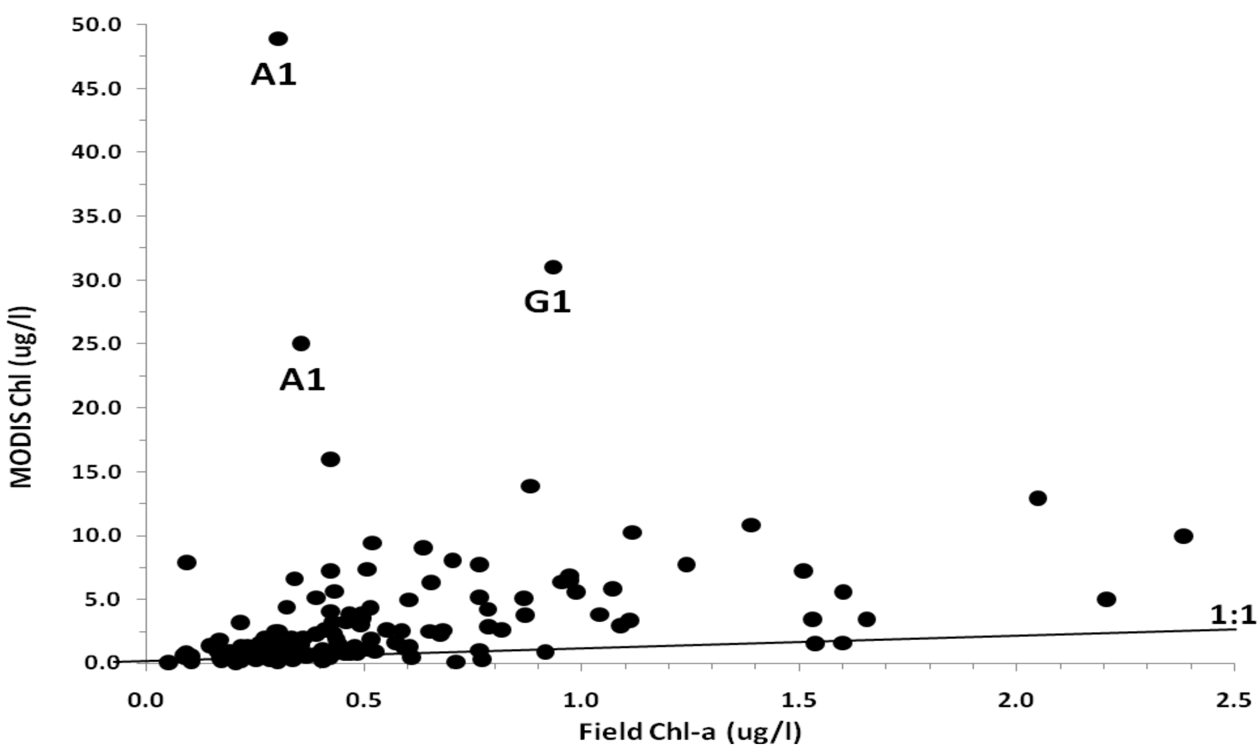
Morel, A. 1974. Optical properties of pure water and pure seawater. In N. G. J. E. Steeman-Nielsen [ed.], Optical aspects of oceanography. p. 1–24.

A., Ras J. & Tièche F. Optical properties of the "clearest" natural waters. Limnol. Oceanogr., 52(1): 217–229.

Morelock, J., Grove, K., Hernández, M.L., 1983. Oceanography and patterns of shelf sediments Mayagüez, Puerto Rico. Journal of Sedimentary Petrology, 53(2): 0371-0381.

Validating OC3 MODIS algorithm for Chl estimation

Remote Sensing Reflectance (R_{rs}) measured with the GER-1500 spectroradiometer from April 2001 to May 2007 in Mayaguez Bay was used to validate the OC3M MODIS algorithm for Chl estimation. The first step consisted in averaging the R_{rs} at the same wavelengths of the three bands used in the algorithm. They are: band 9 (438 – 448 nm), band 10 (483 – 493 nm), and band 12 (546 – 556 nm). Then, the averaged values were used to calculate the concentration of Chl using the algorithm. Finally, the estimated MODIS Chl was compared with the measured (field) Chl-a collected during the same day of the R_{rs} measurements. The analysis shows that in most cases the MODIS algorithm overestimate the Chl-a (see figure below). It was also shown that the highest overestimation occurs in stations closed to rivers mouth, where high suspended sediments and CDOM are found. This work clearly demonstrated how the OC3 MODIS algorithm fails for the estimation of Chl-a in Mayaguez Bay, even when field R_{rs} data are used. This suggests that the NASA Chl product from MODIS images and provided by NASA will provide bad estimates for this region. The next step in this project will be to test this hypothesis.



COASTAL –GILBES' GROUP REPORT

(Performance period: September 1, 2007 to February 29, 2008)

RESEARCH COMPONENT

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):** A journal publication is now in preparation and it will be submitted to Applied Optics. Authors have continue working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.
- **Dollar amount of funds leveraged with CREST funds (during performance period):**
  1. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
  2. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $50,000
- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Patrick Reyes and Ramón Lopez, UPRM-Department of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** José Martinez and Nathlee Hernández, UPRM-Department of Geology (these students worked in a NOAA CREST related topic as part of the course Geol 4049 and 40455, undergraduate research; but they were not directly funded)

- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a. A possible visit of Vilmaliz Rodriguez to his laboratory will be planed and coordinated for the future.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences)
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Validation of MODIS data in Mayaguez Bay was continued. Estimates of Suspended Sediments using bands 1 and 2 (250 m) and Richard Miller's algorithm were compared with field measurements. The first version of site-specific algorithms have also been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. The standard algorithm developed and used by NASA to estimate Chl-a using MODIS was tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data.

Tasks (For year I as per the Milestone Chart)

Task (1) Compare to satellite water leaving products and atmosphere retrievals
Task (2) Intercomparison of the below/above water signals with aircraft and satellite data as available.

This project aims to develop a method to monitor sedimentation processes in a coastal environment by using remote sensing technology. The main objectives of this study were to generate, validate and apply an algorithm to estimate suspended sediment concentration (SS) based on remote sensing reflectance (R_{rs}) and MODIS data. It was expected to establish the relationship between *in situ* measurements of SS and Rrs, to then apply the generated equation to MODIS band 1 and band 2 data (620-670 nm and 841-876 nm, respectively). Considering that R_{rs} values are significantly lower than MODIS data, a second relationship was establish associating band 1 and band 2 of Rrs and MODIS data. The algorithm produced was validated by applying both resultant equations to three MODIS images from which *in situ* data was available. In general, the estimations of the algorithm tended to sub-estimated field measurement values, however, abundance and spatial variations of these estimations responded as expected. An application component was included in this study, which consisted on estimate total river discharge by applying the algorithm produced to an image associated to a significant rain event.

This allowed to calculated total mass for a determined area based on SS concentration. This study provided a base to the desire method but various refinements still need to be applied in the approach for more reliable results. More information can be found in the appended report of Vilmaliz Rodriguez.

Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):** A journal publication is now in preparation and it will be submitted to Applied Optics. Authors have continue working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.
- **Dollar amount of funds leveraged with CREST funds (during performance period):**
  3. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
  4. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $50,000
- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Patrick Reyes and Ramón Lopez, UPRM-Department of Marine Sciences
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- **Students Undergraduate:** José Martinez and Nathlee Hernández, UPRM-Department of Geology (these students worked in a NOAA CREST related topic as part of the course Geol 4049 and 40455, undergraduate research; but they were not directly funded)
- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a. A possible visit of Vilmaliz Rodriguez to his laboratory will be planed and coordinated for the future.

- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences)
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Validation of MODIS data in Mayaguez Bay was continued. Estimates of Suspended Sediments using bands 1 and 2 (250 m) and Richard Miller's algorithm were compared with field measurements. The first version of site-specific algorithms have also been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. The standard algorithm developed and used by NASA to estimate Chl-a using MODIS was tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data.

Tasks (For year I as per the Milestone Chart)

Task (1) Analysis of optical field measurement together with Chl, TSS concentrations

During this time period we have focused on finishing the data processing gathered for the ac-9 instrument. A data set including all the measured parameters were compiled by stations for all eleven cruise from 2004-2007 with there values at the surface and depth. The data includes Remote Sensing Reflectance (R_{rs}), Chlorophyll-a concentration (Chl-a), Total Suspended Solids (TSS) and Chromophoric Dissolved Organic Matter absorption coefficient (a_g at 412 and 443 nm) and the Spectral Slope parameter (S, various ranges) in the UV and visible spectrum. This spectral slope can be further used in remote sensing and in the geochemistry for local CDOM dynamics. Profiles we generated for the time period for the complete cruises, (salinity, Chl-a fluorescence, (absorption and attenuation at 412 and 440 channels). The R_{rs} data was correlated with the ac-9 412 nm absorption channel and CDOM (a_g412) water samples taken at the surface. Good correlations have been observed between R_{rs} and the 412 nm absorption channel, R_{rs} vs. CDOM (a_g) and ac-9 total absorption vs. a_g412. Analyses between the two seasons indicate that differences exist between the measured parameters being only the spectral slope and TSS means similar for both seasons being the bottom resuspention the responsible for this during the rainy season. Laboratory experiments indicate that river water dilution with marine water end members cause a slight decrease in CDOM (a_g375) from its theoretical dilution indicating the possible flocculation of this material. In a similar approach but this time with clays extracted from the river waters a further reduction in a_g375 was observed. This indicates that clay may play an important role during estuarine mixing processes buy adsorbing some of the CDOM to its surface. More information can be found in the appended report of Patrick Reyes.

Task (2) Evolution and tuning of algorithm for Chl retrieval in PR coastal waters

The Moderate Resolution Imaging Spectroradiometer (MODIS) is considered an improved generation of ocean color sensors. However, its validation for coastal monitoring is still underway. The main objective of this research was to validate the accuracy of MODIS to measure phytoplankton Chlorophyll-a (Chl-a) and suspended sediments (SS) in Mayagüez Bay, Puerto Rico. Field measurements of Chl-a and SS were compared with those estimated from MODIS data. A low correlation was found between field and MODIS Chl-a values obtained with both, Terra (R^2=0.0283) and Aqua (R^2=0.0265), satellites and using the standard NASA OC3 algorithm. Since the standard Chl-a product provided by NASA routines was not good for our study area, it was decided to derive and test a local empirical algorithm using MODIS Bands 3 (469 nm) and 4 (555 nm), which provide 500 meter of spatial resolution. The regressed linear equation for B3/B4 ratio and field Chl-a was $y = -0.6614x + 1.4937$ and the $R^2 = 0.3886$; while the logarithmic equation was $y = -0.4939\mathrm{Ln}(x) + 0.7243$ and the $R^2 = 0.3688$. In order to estimate SS with MODIS, Band 1 (645 nm) with 250 meter of spatial resolution was used to validate the algorithm developed by Miller and McKee (2004) in the Gulf of Mexico. However, the suggested equation failed in Mayagüez Bay. A second approach intended to develop a site-specific algorithm for SS using this same band, but low correlation was also found on various testing scenarios. They were R2 = 0.1443 (overall), R2 = 0.0695 (dry season), R2 =0.2788 (rainy season), R2 = 0.0473 (inshore stations), and R2 = 0.0468 (offshore stations). Image processing and analyses clearly demonstrated that MODIS is not the most appropriate ocean color sensor for Mayagüez Bay. Another sensor with better temporal, spatial, and spectral resolutions is still needed for the estimation of Chl-a and SS in coastal waters.

Future Tasks (From the Milestones)

Efforts for developing site-specific algorithms for Chlorophyll-a and suspended sediments will continue. More pre-processing, quality control, and corrections of the bio-optical data are needed before the GIS databases can be developed. Once these steps are completed the data will be exported to ArcView format in order to prepare the databases. Synoptic maps of all parameters will be developed then compiled in the web-base environment ArcIMS. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay. A new doctoral student, Ramón Lopez, has been hired and he will work with this important aspect of the project. A publication of the Vilmaliz Rodriguez work will be submitted to the Applied Optics journal very soon. Patrick Reyes will defend his dissertation and will submit one chapter of the Mayaguez Bay book.

Dynamics of Chromophoric Dissolved Organic Matter (CDOM) in Coastal Tropical
By: Patrick Reyes Pesaresi

Abstract

During this time period we have focused on finishing the data processing gathered for the ac-9 instrument. A data set including all the measured parameters were compiled by stations for all eleven cruise from 2004-2007 with there values at the surface and depth. The data includes Remote Sensing Reflectance (R_{rs}), Chlorophyll-a concentration (Chl-a), Total Suspended Solids (TSS) and Chromophoric Dissolved Organic Matter absorption coefficient (a_g at 412 and 443 nm) and the Spectral Slope parameter (S, various ranges) in the UV and visible spectrum. This spectral slope can be further used in remote sensing and in the geochemistry for local CDOM dynamics. Profiles we generated for the time period for the complete cruises, (salinity, Chl-a fluorescence, (absorption and attenuation at 412 and 440 channels). The R_{rs} data was correlated with the ac-9 412 nm absorption channel and CDOM (a_g412) water samples taken at the surface. Good correlations have been observed between R_{rs} and the 412 nm absorption channel, R_{rs} vs. CDOM (a_g) and ac-9 total absorption vs. a_g412. Analyses between the two seasons indicate that differences exist between the measured parameters being only the spectral slope and TSS means similar for both seasons being the bottom resuspention the responsible for this during the rainy season. Laboratory experiments indicate that river water dilution with marine water end members cause a slight decrease in CDOM (a_g375) from its theoretical dilution indicating the possible flocculation of this material. In a similar approach but this time with clays extracted from the river waters a further reduction in a_g375 was observed. This indicates that clay may play an important role during estuarine mixing processes buy adsorbing some of the CDOM to its surface.

Introduction

During this work period we have focused in finishing the editing and processing all the gathered data for the Mayaguez Bay from 2004-2007 for the ac-9 submersible absorption and attenuation beam meter. The data for the ac-9 was further corrected and was included on the previous developed Excel data set sheet were all the different parameters have been grouped by stations, cruises and season. With this data set it should be possible for other persons using GIS related software to manipulate and generate the required layers for all the measured parameters (CDOM, salinity, Chl-a etc) for the Bay area. Secondly we focused on the R_{rs} data set where we separated the next remote sensing reflectance at the next wavelength 412, 443, 510 and 555 nm. With this values we calculated a series of band ratios ($R_{rs}412/R_{rs}443$, $R_{rs}443/R_{rs}510$, and $R_{rs}510/R_{rs}555$). The relationship between this ratios and the measured total absorption for the ac-9 instrument for the 412 channel, and the measured and CDOM $a_g(412)$ values measured in the laboratory were addressed. Good fits have been found between all the performed relationship with the best found during the rainy season.

Another question we wanted to answer was if it could be possible that the terrestrially derived CDOM could be diluted with marine waters and if it could also be possible that the co-occurring clay material brought by the rivers could be adsorbing CDOM material when they enter in contact with marine waters. This experiments revealed that simple dilution can remove part of the CDOM from solution reducing the a_g(375 nm). In a similar experiment but this time using clay material extracted from the river waters, indicate that the clay particles reduce even further the a_g375 than the dilution experiment alone. This fact indicates that clay material brought at the same time with the terrestrial CDOM can be adsorbed to these particles during estuarine mixing and that even during mixing some of the material can be lost possible due to flocculation.

Material and methods

Ancillary data:

Files containing the precipitation data For the Añasco, Guanajibo and Yagüez River watershed were taken from the national whether service Web page and the River flow data was downloaded from the USGS River Flow web page. Precipitation and river flow graphs were done for the study period. After checking the natural fluctuations due to precipitation and hence River flow we divided the seasons between dry and rainy season. The cruises were divided between the rainy and dry season as the months were the river discharge were on average more that 15 m^3/s for the three previous days. In this case July that was taken as a dry month was included in the data set of the cruises of the rainy season. ANOVA Statistical analysis showed that their where significantly differences between the rainy and dry seasons no matter the time scale that was evaluated.(three, one week, two weeks an monthly). A time series graph was generated for the precipitation and River flow (Appendix)

Ac-9 data correction and editing.

After binning the ac-9 profile data at 0.5 meter depth, the raw data was corrected with the instrument calibration files for temperature and water blank. After this step the data was further corrected by the in *situ* measured salinity and temperature and by subtracting the 715 nm channel for scattering at each depth (Pegau et al., 1997). This correction was done for each of the absorption (a) channel and attenuation (c) channel no scattering correction has to be performed for the attenuation channel. The final values were then organized by stations generating 9 columns for absorption (412, 443,488, 510, 532, 555, 650, 676 and 715 nm) and the same channel for attenuation, binned at 0.5 meter depth. I further refined my data set and isolated the data only for only 412 a and c and 440 a and c channel since this values are the ones relevant for my research.

Remote sensing reflectance

Remote sensing reflectance was evaluated as a tool for the estimate of CDOM absorption. After calculating and correcting the Remote Sensing Reflectance for each station. We proceeded for our analysis to calculate an average value at (412,443, 510 and 555 nm) by taking the R_{rs} values five nanometers up and down the mention values. Then with the calculated averages we calculated a band ration between (R_{rs}412/R_{rs}443, R_{rs}443/R_{rs}510, and R_{rs}510/R_{rs}555) as described by (D'Sa and Miller 2007). This was done to evaluate the relationship between CDOM a_g (412) at one meter depth and the total absorption measured by the ac-9 412 nm channel also at one meter depth. The relationship between for CDOM a_g 412 and the measured values for the ac-9 412 total absorptions were also evaluated.

CDOM dilution and clay adsorption experiments:

Four liters of water at the offshore Y2 Station (Marine water) and a same volume for the Anasco river were collected in amber ashed crystal bottles. The samples were immediately were filtered trough ashed GF/F glass fiber filters and refrigerated. A series of progressive dilutions were made between the marine and river water. The samples were left at room temperature overnight, and the next day the samples were re-filtered through the same GF/F filters and CDOM absorption was determine for each of the 9 dilution and two end members in duplicates. CDOM a_g375 was calculated for each dilution the final salinity was measured.

In a second experiment a similar approach was conducted, but this time the Añasco river water end member was amended with 0.150 mg of clay material recover from the same river in a 208 liter drum and was left to settle by gravity after a week. The Clay material was then oven dried at 60^{o}C and pulverized with a mortar and pestle. Two replicate dilution of one liter filter water were made by adding the weighted clay material. The next day dilution were made using this dilution stock After a day of equilibration at room temperature the samples were re-filtered and the optical density measured. Then the salinity for each dilution was determined by an YSI portable salinometer.

Statistical analysis:

For all the evaluated parameters number of Parsons regression analysis and ANOVA analysis have been performed.

Results

In the performed statistical analysis seasonality was indeed observed for the measured parameters. Significantly differences were found between the rainy and dry season for salinity, a_g375 and Chl-a. In the case of the spectral slopes and TSS no significant differences were found between seasons. From an inshore to offshore stations salinity, TSS, Chl-a and CDOM a_g375 were significantly different. The Spectral slope parameters were not significantly different between the rainy and dry season. (Table: 1-5)

For the laboratory CDOM experiments it was found that simple dilution between marine and river end members can remove a fraction of this material and that CDOM does not behaves in a conservative way during mixing. In the next experiment were clay material was added to river waters and this solution mixed with marine water end members it was found that the loss of CDOM absorption (a_g375) was even larger an that this could be due to adsorption of the CDOM material to clays (Figure: 6)

Table: 1 Salinity ANOVA between Season and Inshore- Offshore stations

Salinity		
Dry Season Inshore Offshore	**p = 0.15724 (NS)**	**At the 0.05 The means are NOT significantly different.**
Rainy Season Inshore Offshore	**p = 2.14605E-5*** **	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 7.45395E-10*** **	**At the 0.05 The means are significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 2 Total suspended solids ANOVA between Season and Inshore- Offshore stations

TSS		
Dry Season Inshore Offshore	**p = 4.24301E-5*** **	**At the 0.05 The means are significantly different**
Rainy Season Inshore Offshore	**p = 0.00519 ***	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 0.40295 (NS)**	**At the 0.05 The means are NOT significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 3 Chlorophyll-a ANOVA between Season and Inshore- Offshore stations

Chlorophyll-a		
Dry Season Inshore Offshore	**p = 1.95523E-5*** **	**At the 0.05 The means are significantly different**
Rainy Season Inshore Offshore	**p = 1.2221E-7*** **	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 0.14865 (NS)**	**At the 0.05 The means are NOT significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 4 Spectral Slope ANOVA between Season and Inshore- Offshore stations

Spectral slope (375-400 nm)		
Dry Season **Inshore** **Offshore**	**p = 0.06508(NS)**	**At the 0.05 The means are NOT significantly different.**
Rainy Season **Inshore** **Offshore**	**p = 0.08903(NS)**	**At the 0.05 The means are NOT significantly different.**
Dry vs Rainy	**p = 0.02784 ***	**At the 0.05 The means are significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Table: 5 CDOM ANOVA between Season and Inshore- Offshore stations

CDOM a_g375 surface only		
Dry Season **Inshore** **Offshore**	**p = 3.09064E-6*** **	**At the 0.05 The means are significantly different.**
Rainy Season **Inshore** **Offshore**	**p = 2.2949E-6*** **	**At the 0.05 The means are significantly different.**
Dry vs Rainy	**p = 6.89081E-5**** **	**At the 0.05 The means are significantly different.**

Statistical significace
NS (p>0.05)
weak (0.01<p<0.05)*
moderate (p< 0.01)**
strong (p<. 001)***

Figure: 1 Dilution diagram experiment with Marine and Anasco River end member

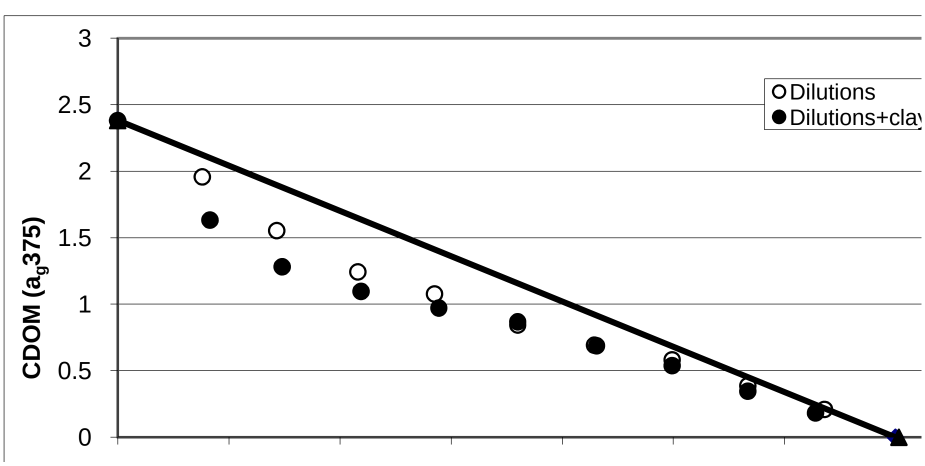


Figure: 2 Remote sensing reflectance vs. ac-9 412 channel correlation

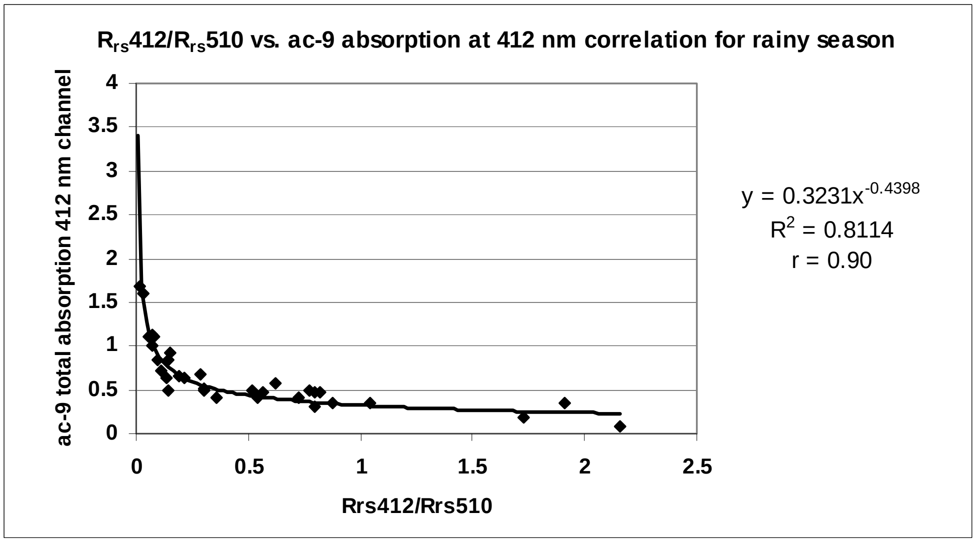


Figure: 3 Remote sensing reflectance vs. a_g 412 correlation

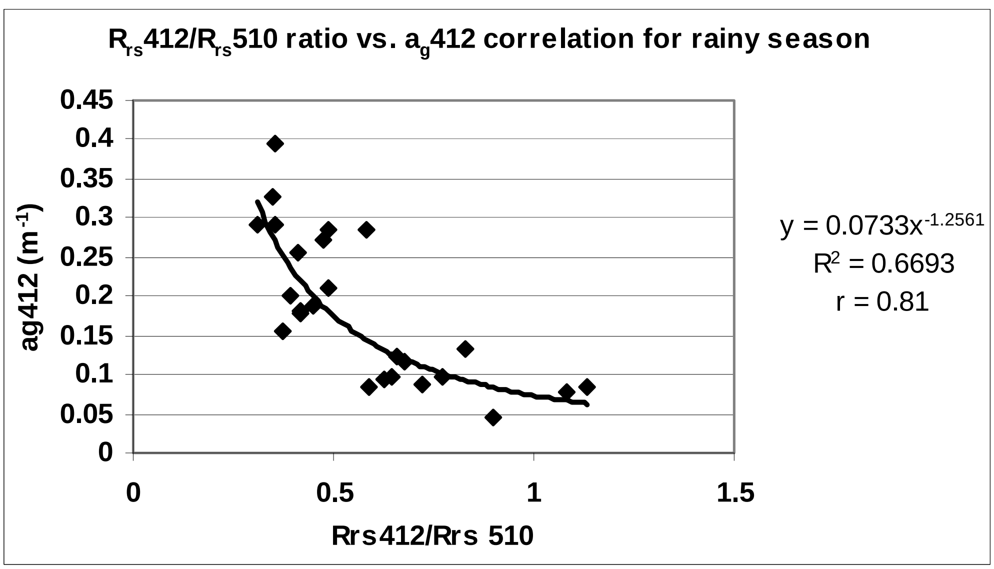


Figure: 4 AC-9 412 absorption channel vs. a_g 412 correlation for the rainy season

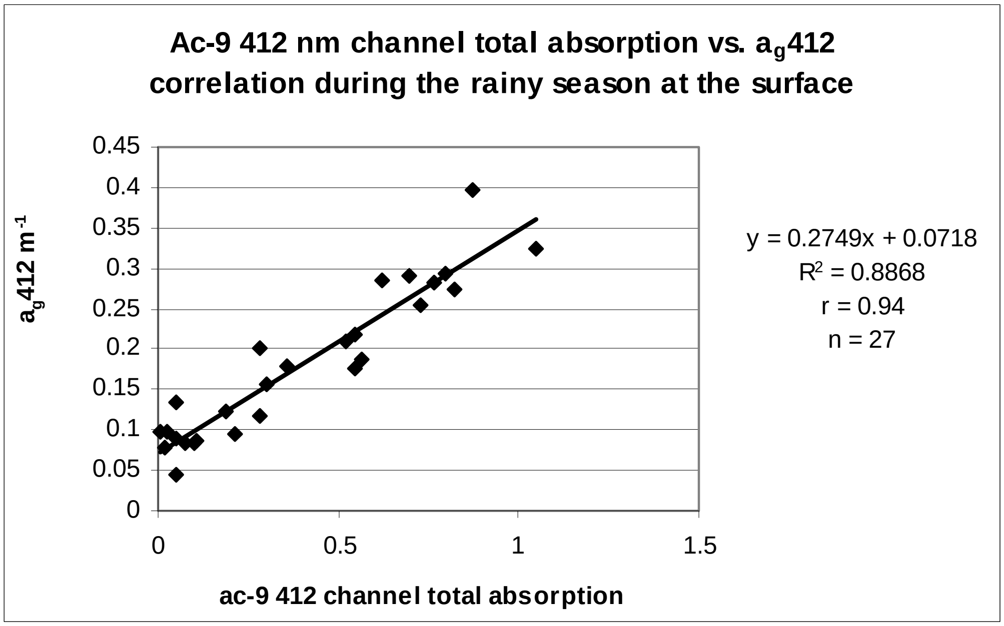
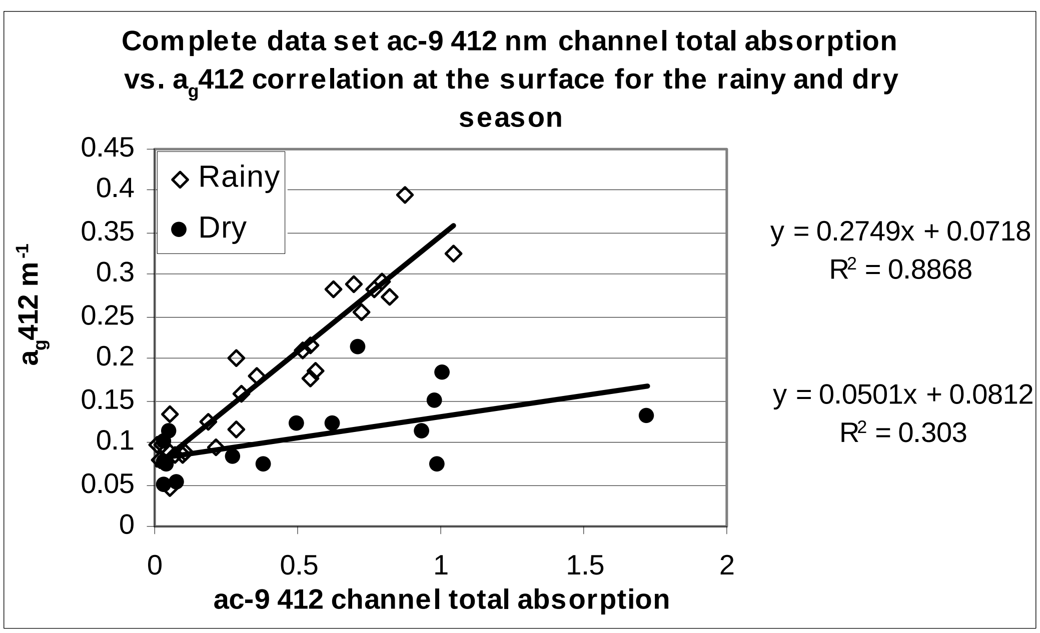


Figure: 5 AC-9 412 absorption channel vs. a_g 412 correlation for both seasons



Discussion

For precipitation and River flow data it was found a marked seasonality are observed for both cases. Since our cruises could no be performed on a regular basis this was one of the criteria to divided the cruises between the rainy and dry season. Seasonality has also been observed by a number of other works in the bay (Alfaro, 2002, Parilla, 1996, Rosado, 2000, Gilbes, 1992; Gilbes et al., 1996). I is observed that a marked seasonality is observed between season during the rainy season salinity are markedly lower due to local river flow with the consequence of higher TSS and a_g375. increasing from an inshore offshore gradient. During the dry season the salinities are higher but in the case of TSS the average values no significantly different from those of the rainy season mining that other processes such as resuspention during the winter months causes that bottom sediment are distributed in the water column. During this period is when the river flows and lower so that the TSS must come from the shallow bay area that are influence by strong currents and wave action. This fact could also explain that CDOM Spectral slope or not significantly different between seasons. And that CDOM material might come from bottom sediments due to this event characteristic of the winter season.

Our analysis indicates that the total absorption 412 channel of the ac-9 channel is well correlated with the calculated with the R_{rs} band ratio at ($R_{rs}412/R_{rs}510$), in a similar manner the a_g412 is also well correlated with the same bands ratios(Figure 7 and 8). In a similar manner a_g412 and the total absorption values for the ac-9 are also well correlated only during the rainy season only (Figure: 9). During the dry season other processes no related to the local rivers might be involved since the lack of correlation between a_g412 and ac-total absorption (Figure 10).

The laboratory experiment indicate that dilution between end members from marine waters and Añasco River can cause a reduction a_g375 absorption coefficient suggesting that some process like flocculation might be the responsible (Figure: 6). This reduction in CDOM signal was more evident in the lower ranges of salinity. This indicates that during the initial mixing at the lower salinity same of this CDOM material can be lost due to flocculation. In a similar experiment (Sholkowitz, 1976) recorded that during estuarine mixing between dissolved organic and inorganic mater flocculation of organic resulted. But in other experiment no flocculation effects were recorded by (Preston and Riley 1982) using a similar approach. In our experiment only dilution had a reducing effect of the CDOM signal at 375 nm indicating the flocculation of this material that was removed from the solution after filtration process.

CDOM is mainly compose of humic and fulvic acids (Kirk, 1994) and in the coastal environment terrestrial derived CDOM dominates in the aquatic environment. Humic and fulvic acids are known to react with clay material in the soils (Ghabbour et al., 2004; Krestschmar et al., 1997. Tachitzky et al., 1993). The humic acids-clay interactions are influence by a verity of factor like the nature of the clay (kaolinite, illite, montmorillonite etc.) ionic strength, pH, and cations associated to the surfaces of the clays and temperature. In a similar manner the humic acids are affected by ionic strength and pH this can cause changes in the molecule conformation, charge and solubility increasing or decreasing its affinity to the clay material. X-Ray Diffraction performed to the collected water solids from the Anasco River reveled that (kaolinite, illite, montmorillonite) are being transported in the river waters. And that the clays found in the bottom sediments of the Mayaguez Bay (Ramirez, personal communication) are composed of the same clay material.

In a second experiment with another set of dilution but this time to the river waters we added solid material extracted from the same river, a reduction in (a_g375) was again observed and also was noticed in the lower salinity range (Figure: 6). So it is possible that flocculation decreases the CDOM signal during mixing and increases in the presence of solid material transported in river waters.

Conclusion

Remote sensing reflectance can be used as an effective tool to monitor the dynamics of CDOM in the Mayaguez Bay area. Marked differences were observed between the rainy and dry season for most of the measured parameters. The laboratory experiments give a new insight to the geochemistry of the clay-CDOM interactions derived from the terrestrial environment when they enter in contact with marine water. This result is promising since this result has never been address for the Mayaguez Bay. Other biological and bio-optical implication could be explained.

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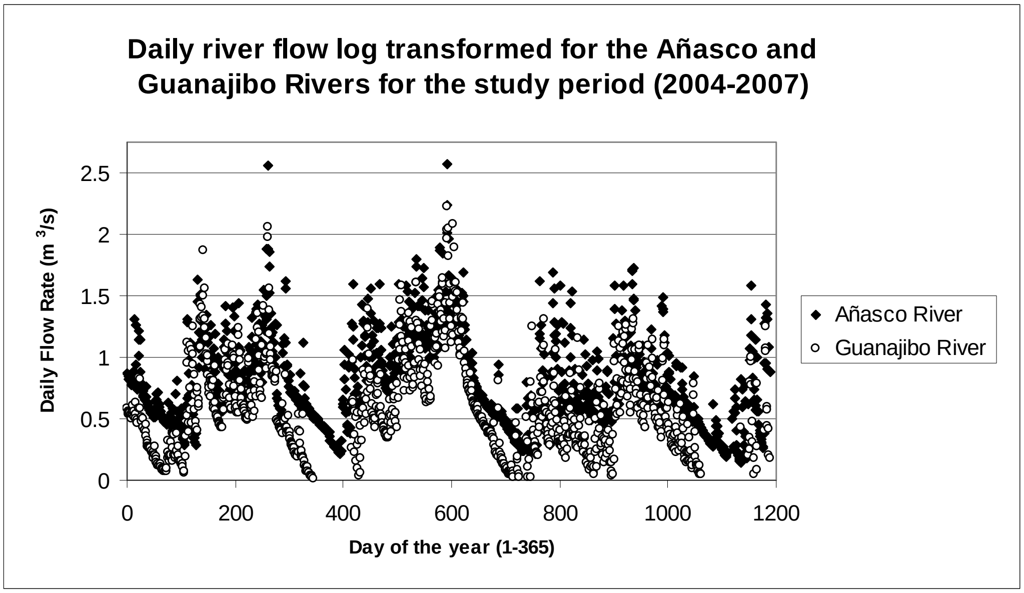
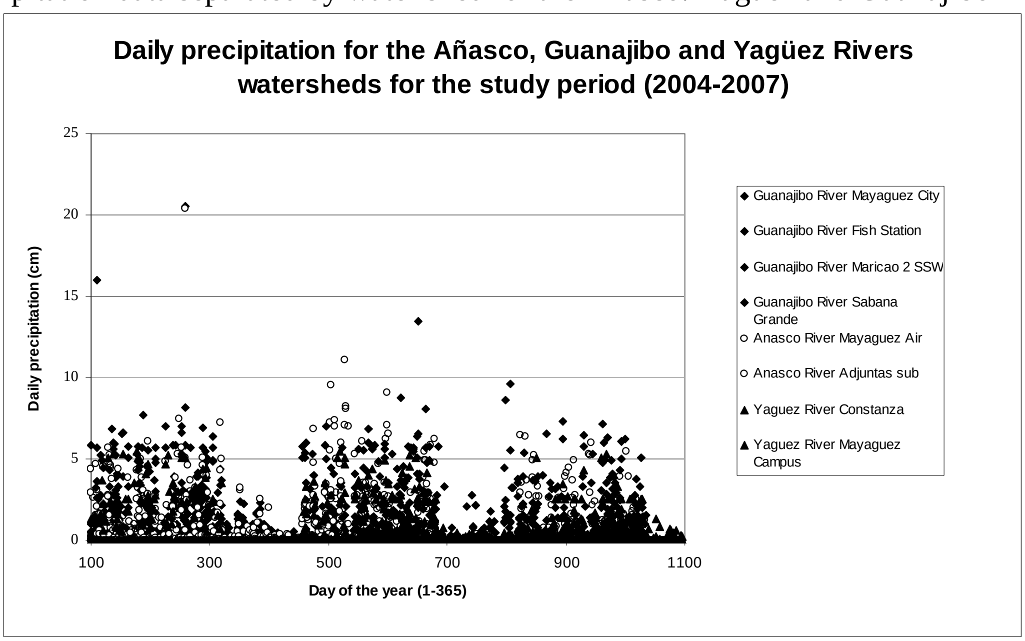
Appendix

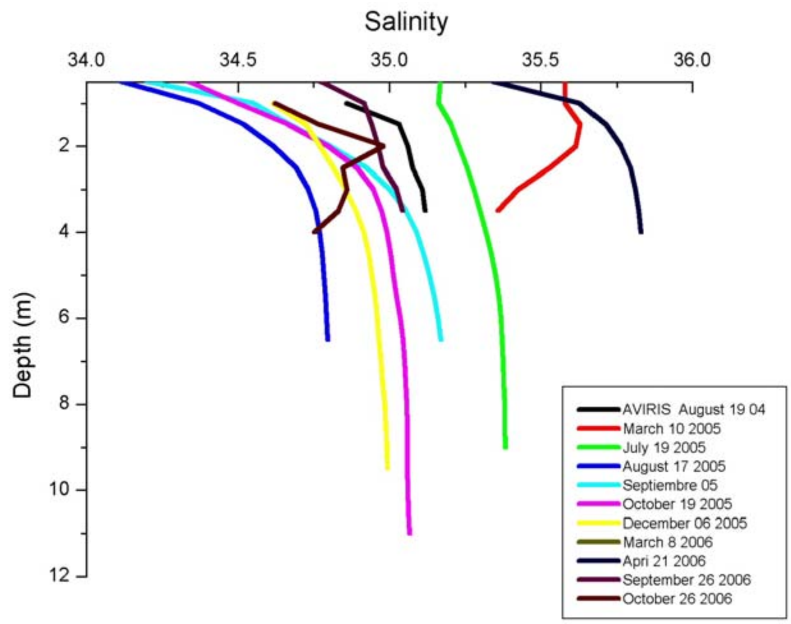
River flow for the Añasco and Guanajibo no monitoring station is located in the Yagüez River



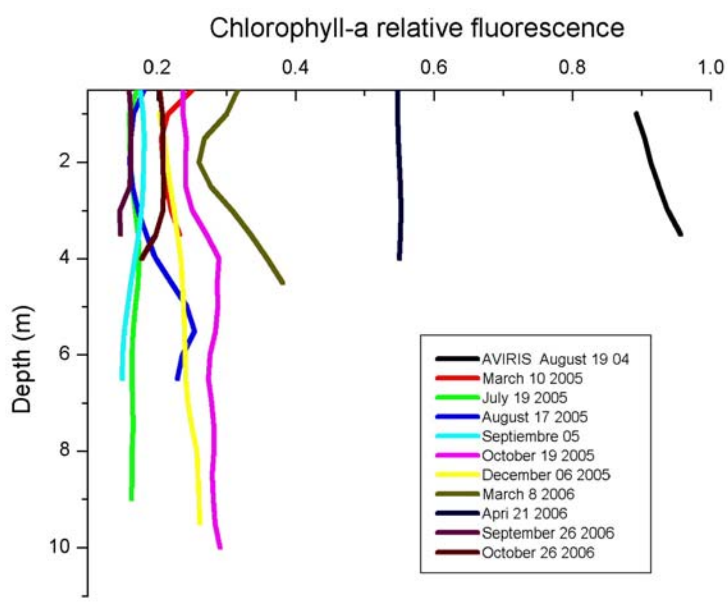
Precipitation data separated by water shed for the Añasco. Yagüez and Guanajibo Rivers



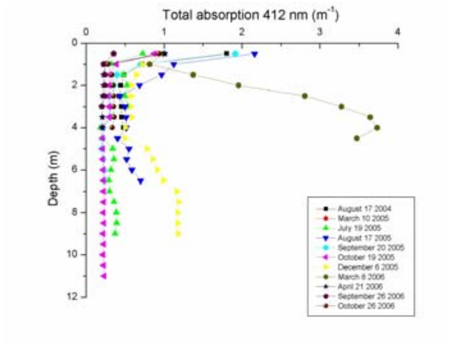
Salinity Profiles for the A1 stations



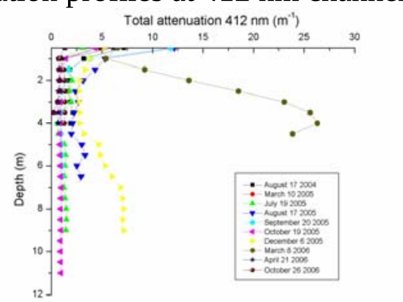
Chlorophyll-a profiles for the A1 station



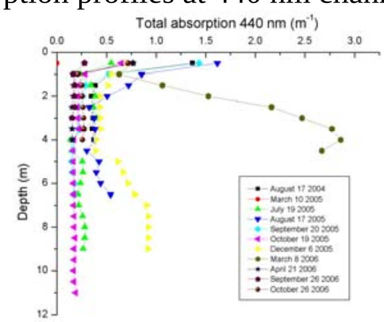
Total absorption profiles at 412 nm channel for the A1



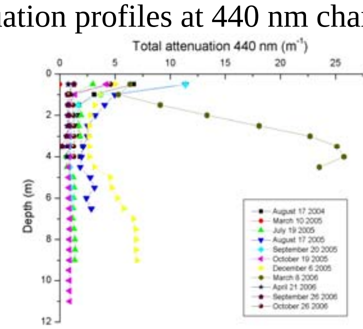
Total attenuation profiles at 412 nm channel for the A1



Total absorption profiles at 440 nm channel for the A1



Total attenuation profiles at 440 nm channel for the A1



DEVELOPING A METHOD TO MONITOR SEDIMENTATION PROCESSES IN MAYAGÜEZ BAY USING MODIS DATA

Vilmaliz Rodríguez-Guzmán & Fernando Gilbes-Santaella

ABSTRACT

This project aims to develop a method to monitor sedimentation processes in a coastal environment by using remote sensing technology. The main objectives of this study were to generate, validate and apply an algorithm to estimate suspended sediment concentration (SS) based on remote sensing reflectance (R_{rs}) and MODIS data. It was expected to establish the relationship between *in situ* measurements of SS and Rrs, to then apply the generated equation to MODIS band 1 and band 2 data (620-670 nm and 841-876 nm, respectively). Considering that R_{rs} values are significantly lower than MODIS data, a second relationship was establish associating band 1 and band 2 of Rrs and MODIS data. The algorithm produced was validated by applying both resultant equations to three MODIS images from which *in situ* data was available. In general, the estimations of the algorithm tended to sub-estimated field measurement values, however, abundance and spatial variations of these estimations responded as expected. An application component was included in this study, which consisted on estimate total river discharge by applying the algorithm produced to an image associated to a significant rain event. This allowed to calculated total mass for a determined area based on SS concentration. This study provided a base to the desire method but various refinements still need to be applied in the approach for more reliable results.

Introduction

The Mayagüez Bay is located at the west coast of Puerto Rico, delimited by Mayagüez and Añasco cities. Many biological, chemical and geomorphologic processes are affected by the distribution and abundance of suspended sediments in this bay. Suspended Sediments (SS) consist of material composed of clasts derived from pre-existing rocks that can be transport in suspension. The concentration of SS is considered one of the most important water quality parameters (Wang et al., 2005) and can produce non-point source pollution. In coastal environment the presence of SS reduces the amount of light available through the water column, producing habitat detrimentation.

Spatial and temporal variations in SS concentration can be the effect of anthropogenic or natural factors. Various studies have been developed to better understand and define the processes affecting these variations (Grove, 1977; Miller et al. 1994; Gilbes et al. 1996). It has been determined that the presence of SS in the bay is highly influence by resuspension events (Morelock, 1983; Miller et al. 1994), additionally to the rivers discharging in the area (Grande Añasco River, Yagüez River and Guanajibo River). A study of the sedimentation processes in the coastal environment will define aspects associated to the production, transport or deposition of sediments. However, all the field work necessary to monitor these processes could require plenty of money, effort and time, factors that limit the development of this type of studies. This limitation is reduced by incorporating components based on remote sensing, where desire information can be obtained from spectral data. Before using remote sensing data for a specific application, a relationship between the parameters of interest (e.g. SS) and spectral data must be defined. This study expects to establish the relationship between *in situ* measurements of SS concentration and Remote Sensing reflectance (R_{rs}) with MODIS bands 1 and 2 data.

The present study is focused on develop a method to monitor the distribution and abundance of SS associated to river discharge using MODIS data. To accomplish this, three main objectives were defined: (1) Develop a site-specific algorithm to estimate SS concentration based on MODIS data, (2) Validate the generated algorithm using *in situ* SS measurements (3) Estimate total river discharge for a significant rain event by applying the generated algorithm to day after a storm event occurred.

Methodology

Two of the parameters used for the development of the algorithm were measured during various research cruises in the study area. In each visit around six to eight stations are monitored for SS concentration and Remote Sensing reflectance (R_{rs}) with a spectoradiometer (GER 1500). The SS data to be used in this study corresponded to all the material larger than 0.7 μm collected at approximately 1 meter depth. With the GER 1500 we obtained spectral information of the water surface from about 370nm to 1,000 nm. Considering that the measurements of this instrument were going to be correlated to MODIS band 1 and 2 data, mean values were calculated between the ranges of 620-670nm and 841-876nm corresponding to band 1 and 2, respectively.

MODIS DATA

Images corresponding to the dates of the research cruises were downloaded through a NASA Internet server called Landweb. The product selected was MOD02QKM, which includes reflectance and radiance information of MODIS first two bands.

Three pre-processing routines were applied to the images before they were used for analysis: georeferentiation, spatial subset and atmospheric correction. The image processing software used was ENVI v. 3.4, which provided the tools necessary for this pre-processing part and for the analysis. All the images were georeferenced as UTM NAD83 for Puerto Rico region. This georefentiation was validated by taking, with a GPS unit, 17 points along the shoreline of Mayagüez Bay and then overlaying these points on a georeferenced image (band 2) to then see how effectively they represented what it was observed in the image (Fig. 1). After the georefentiation, an atmospheric correction was applied. For this process it was used the pre-defined routine called “Dark Substract” with the “User Value” option. In this case the band 2 was used to select the darkest pixel and defined that as the “User Value”.

ALGORITHM DEVELOPMENT

The final product of this algorithm will be able to estimate SS concentration in Mayagüez Bay based on MODIS data (MOD02QKM). Three data sets were used for the development of the algorithm, (1) the data obtained with the GER 1500, (2) the SS measured and (3) MODIS reflectance values of the pre-processed images. Firstly, the relationship between the R_{rs} and the SS concentration was established and defined by an equation. Then, as an intermediate part of the algorithm, it was necessary to also establish the relationship between R_{rs} and MODIS reflectance. The MODIS reflectance values used were obtained from three of the most cloud and errors free images; the values were extracted from the pixels corresponded to stations monitored for R_{rs}. Defining the relationship between these parameters helped to convert MODIS reflectance to R_{rs} equivalent values, step necessary to be able to apply the equation that estimates SS concentration from R_{rs}.

ALGORITHM VALIDATION

Previously developed equations were applied to six images corresponding to dates of research cruises. The equations were defined in ENVI as follows:

$$0.4033 * \text{float (B1)} - 0.006 \quad (1)$$

where, B1=MODIS band 1

$$452.41 * \text{float (B1)} + 2.9603 \quad (2)$$

where, B1=MODIS band 1

Finally, the product of these equations was compared with the *in situ* measurements to determine the error of the estimations.

SIGNIFICANT RAIN EVENTS

The developed algorithm was applied to an image representative of the day after a significant rain event occurred. The days with significant rain were identified using daily river discharge data of two gauges stations located within the Mayagüez Bay watershed (Fig. 2). For the Añasco river the station used was the 50144000 and for the Guanajibo river the 50138000. The Yagüez River does not have any active gauge station therefore it could not be included in this analysis. For each station it was considered the historic data, and it was determined the daily mean discharge and the standard deviation for each river. Then, two hydrographs were plotted using mean daily discharge of 2005 and the historic mean discharge and the standard deviations were included as lines. The percent of standard deviation was defined with "trial and error", until the line reached the base flow. Using this method it was possible to identified significant rain events, mean flows and base flows within 2005.

Various images corresponding to days after a significant rain event occurred were examined for clouds and instrument errors. The image selected was from October 26, 2005 and it was pre-processed using the same methods described before and equations (1) and (2) were applied. For this analysis it was necessary to apply a third equation to convert SS concentration to total mass, assuming a volume of water of 31,250 m^3 per pixel (length=250m; width=250m; depth=0.5m).

$$31.25 * \text{float (B1)} \quad (3)$$

where, B1= equation (2) product

The application of this equation generates a product of SS mass (kg) for all the volume of water within each pixel until 0.5m depth, assuming and homogenous concentration in all the area. A polygon was defined delimiting the Mayagüez Bay and all the values within that area were summed.

Results and Discussion

ALGORITHM DEVELOPMENT

A significant relationship (R^2=0.72; n=38) was defined between SS (mg/l) and R_{rs} of both spectral bands (620-670nm and 841-876nm) (Fig. 3). Observing this correlation, it is evident the limited amount of measurements corresponding to conditions of high concentrations; most of these measurements are less than 15 mg/l. In this case, it is difficult to know how representative is the linear equation defined to the actual relation between these two parameters. Additionally, this fact indicates that the general concentration of SS in the bay is relatively low and, therefore it limits the development of this type of studies because it is more difficult to detect the signal of interest.

Considering that both bands showed a good relationship with the measurements of SS, a single relationship was established using both bands in order to improve the algorithm. The result of this approach is illustrated in Fig. 4, where it can be observed that the estimated values are very close to the observations and the R^2 increased to 0.78.

In general, it was observed that MODIS reflectance values were considerable higher than the R_{rs}, therefore it was not possible to directly apply the previously defined equation to MODIS data. The relationship between R_{rs} and MODIS data was defined finding a significant relationship (R^2=0.92; n=10) with band 1 and a poor relationship with band 2 (R^2=0.13; n=7) (Fig. 5). This result indicates that the band 2 should not be integrated in the algorithm because the signal in this region is highly affected by the atmosphere.

ALGORITHM VALIDATION

For validation purposes, equations (1) and (2) were applied to six images corresponding to cruises dates that were not included in the previous analysis (Fig. 6). These products showed an expected spatial variability of SS, where river discharge dominates the Añasco River area during the rainy season, and re-suspension events dominates during the dry season near the Guanajibo River. In various products can be observed what it seems to be the effect of the bottom (Fig. 6d), but a more specific analysis including the bathymetry of the area have to be develop.

The comparison of the estimated values (extracted from the products generated) with *in situ* measurements showed that even though the estimations are within the expected range, they tended to sub-estimate the observations (Fig. 7). This plot showed that the relative changes are similar in both lines indicating that the signal detected by MODIS sensor in band 1 is highly affected by SS concentration. The limitations of this algorithm can be attributed to various factors: (1) the lack of data representative of high SS concentrations, (2) the sensor is not capable of detecting the SS signal in under low concentrations conditions and (3) the effect of the bottom and/or atmosphere in the signal.

ALGORITHM APPLICABILITY

This section shows the results of the application component of this study, which it attempted to estimate SS river discharge of a significant rainy event. For 2005 a total of 83 days were identified with significant rainy events; this represents a 23 percent of the total of days in one year. Based on previous knowledge, this percent is reasonable. The selected image for this analysis was from October 26, 2005, and the flow discharge associated to this event was 718 cf/s in Grande de Añasco River (USGS). After applying the algorithm developed, the product showed that the higher concentration of SS is associated to the discharge of this river, while a big plume is observed near the Guanajibo River (Fig. 8). Total SS discharge associated to this event was estimated as 392 metric Tons. The main purpose of this part of the study was to develop a method using ENVI to calculate SS discharge from the algorithm product. In future work, the values obtained will be discussed based published information by the USGS.

Conclusions

The development of an algorithm capable of estimate SS concentration in Mayagüez Bay is a very useful mechanism that will reduce the field work and will allow the development of studies covering larger areas. Remote Sensing techniques provide tools and advantages that helped in the development of a base method to monitor SS spatial and temporal variations in Mayagüez Bay. This study described a method that combines parameters of different origin (SS, R_{rs} and MODIS reflectance) to generate a product of SS.

It was determined that the geometric and radiometric corrections that are included during the pre-process are crucial for this type of analysis. The atmospheric correction must be a cautious process given that a poor correction has a negative impact in the final results. It was determine that the pre-defined routine in ENVI to georeference MODIS images is reliable.

Although the initial approach in the development of the algorithm, included both MODIS bands 1 and 2, the results indicated that band 2 should not be included in this type of studies, especially if conditions are dominated by low SS concentrations. No relationship could be determined between MODIS band 2 and R_{rs} (mean 841-876). The algorithm estimations were able to detect spatial variations associated to SS distribution, but the estimated values tended to sub-estimated the *in situ* measurements. The estimation are within an acceptable range considering the lack of data corresponding to high concentrations, the weak signal present in this area, and other factors such as bottom and atmospheric effects. The results of this study support the development of a Remote Sensing based method to monitor important sedimentation processes, further analysis will be incorporated for full application of the method.

Aknoledgements

This study was developed in collaboration with Francisco Torres-Vega. Special thanks to Patrick Reyes and José Martinez for helping in getting and processing part the data. Finally, thanks to all the people that collaborate in the field and laboratory work.

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Apendix

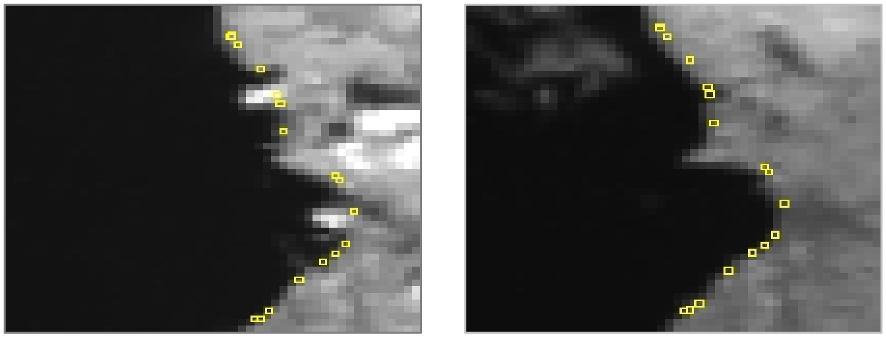


Figure 1. Georeferentiation validation; October 19, 2005 (left) y December 6, 2005 (right).

Figure 2. Study area hydrography with USGS stations

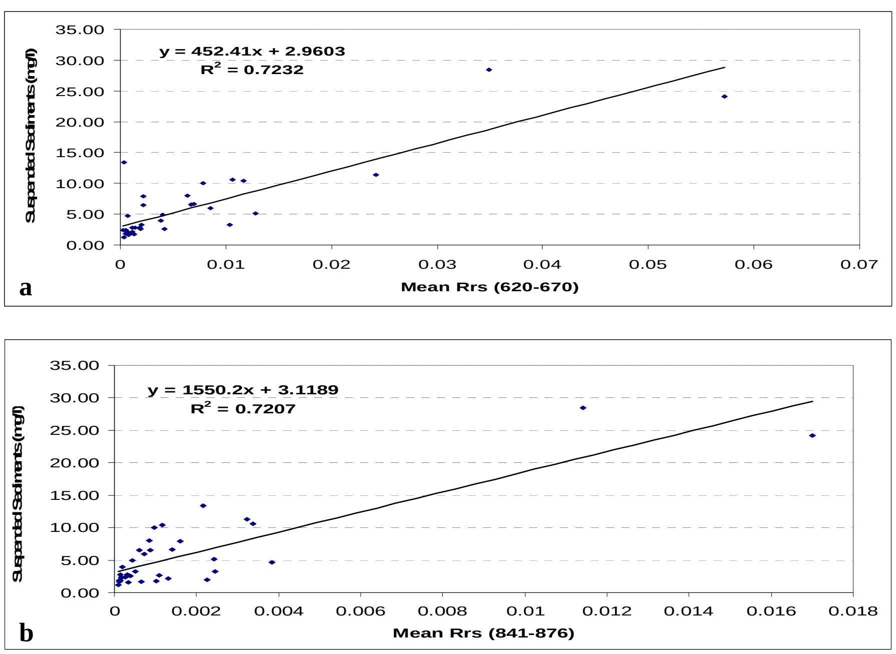


Figure 3: Relationship between SS conc and R_{rs} based on MODIS (a)band 1 and (b)band 2

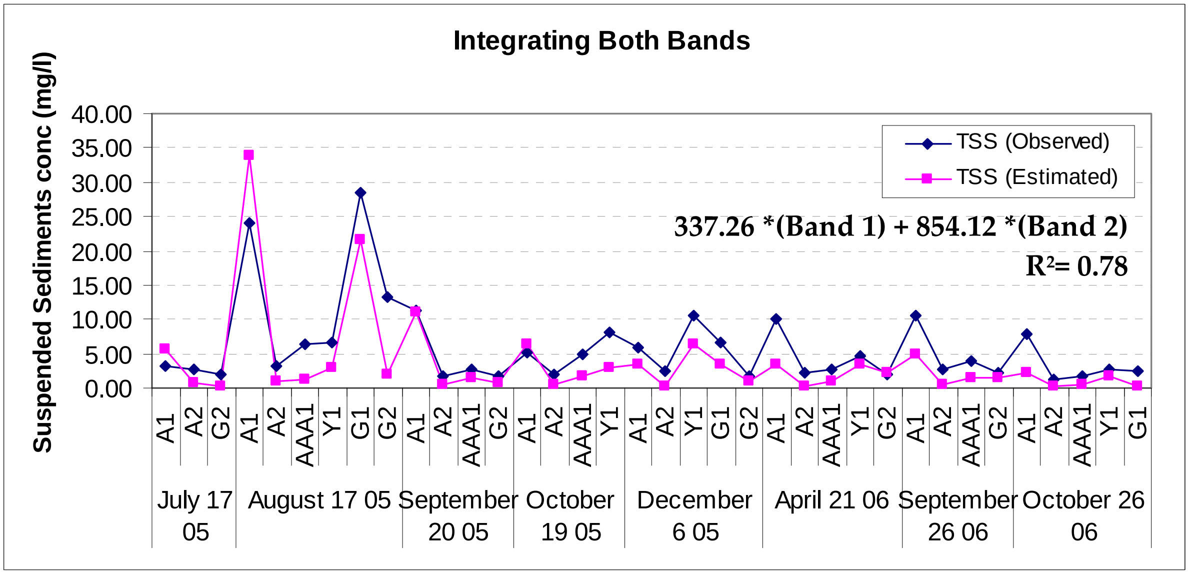


Figure 4. Results of integrating both bands (1 and 2) in the same equation (Spectoradiometer data)

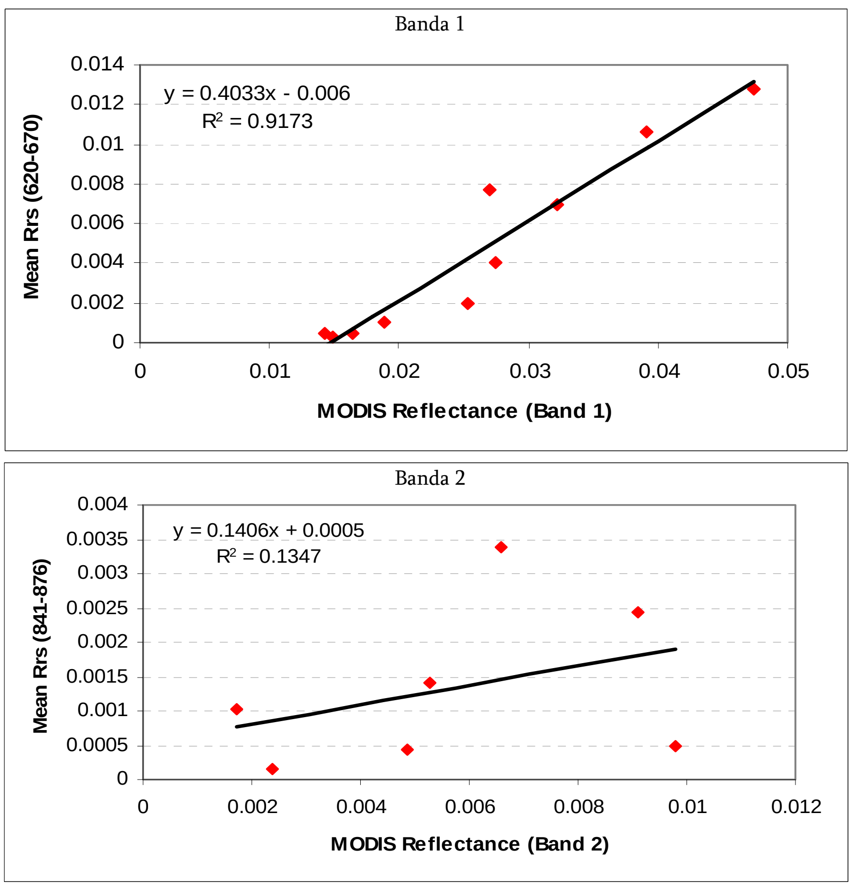
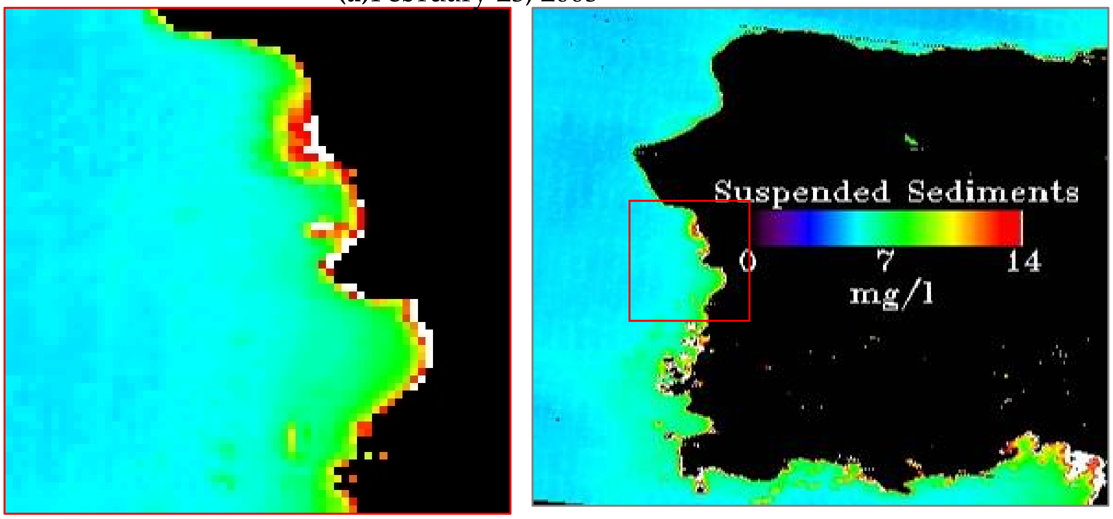
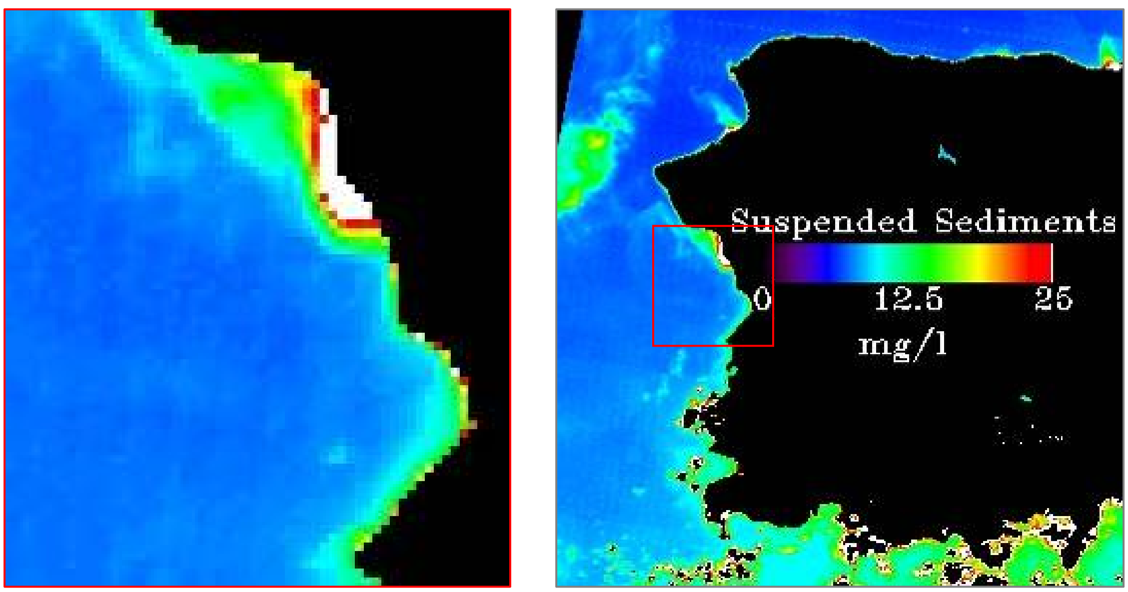


Figure 5. Relationship between R_{rs} and MODIS reflectance

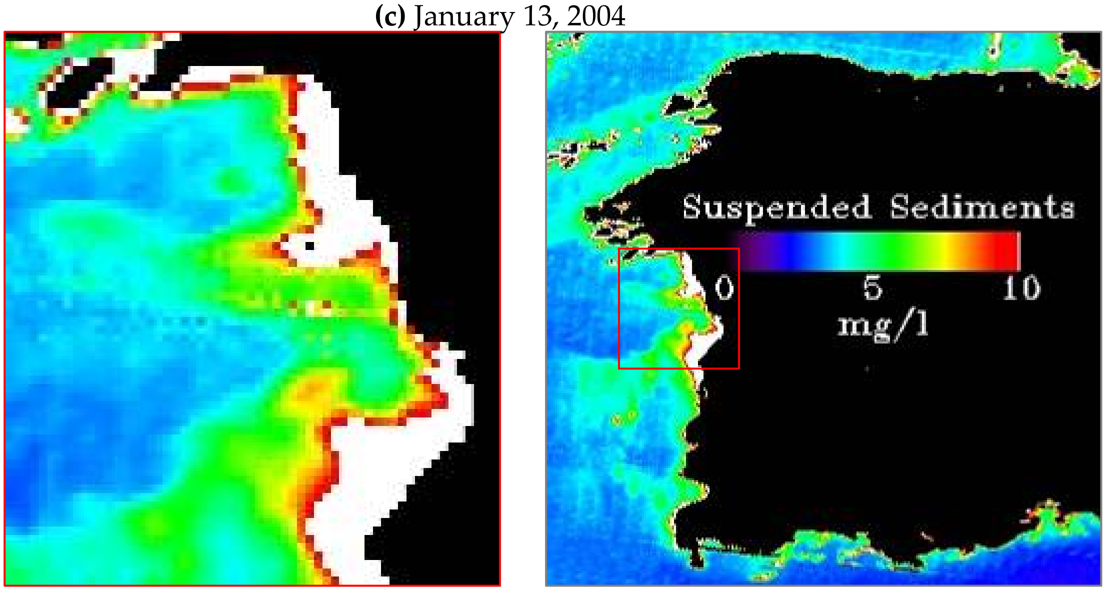
(a) February 23, 2003



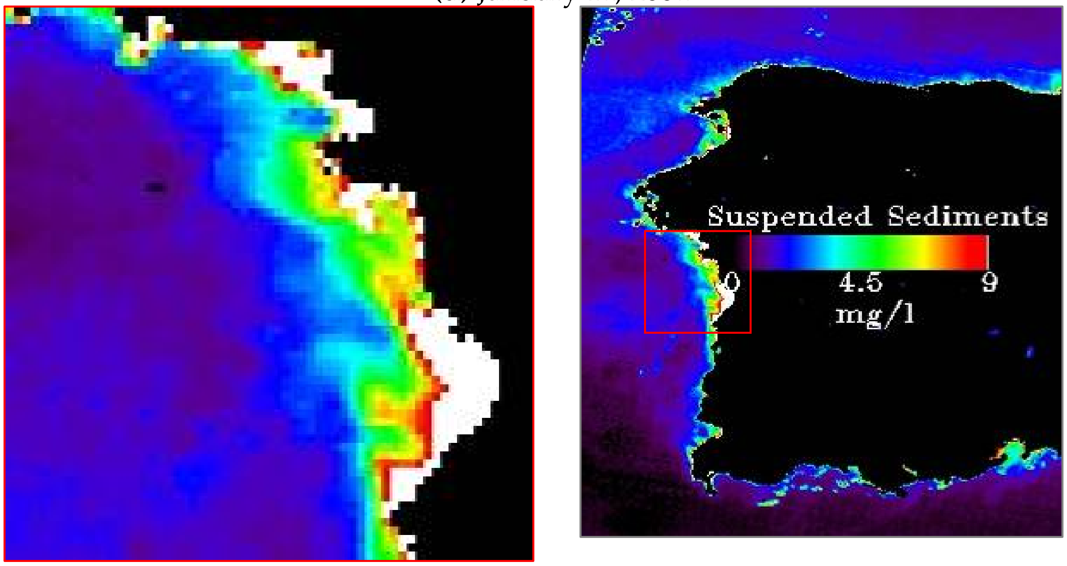
(b) October 7, 2003



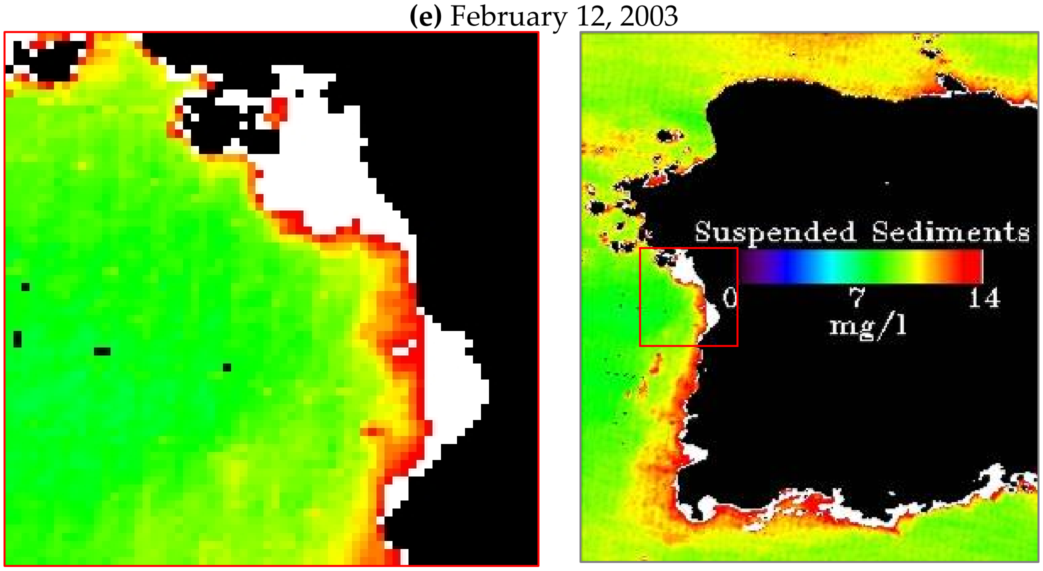
(c) January 13, 2004



(d) January 14, 2004



(e) February 12, 2003



(f) March 8, 2006

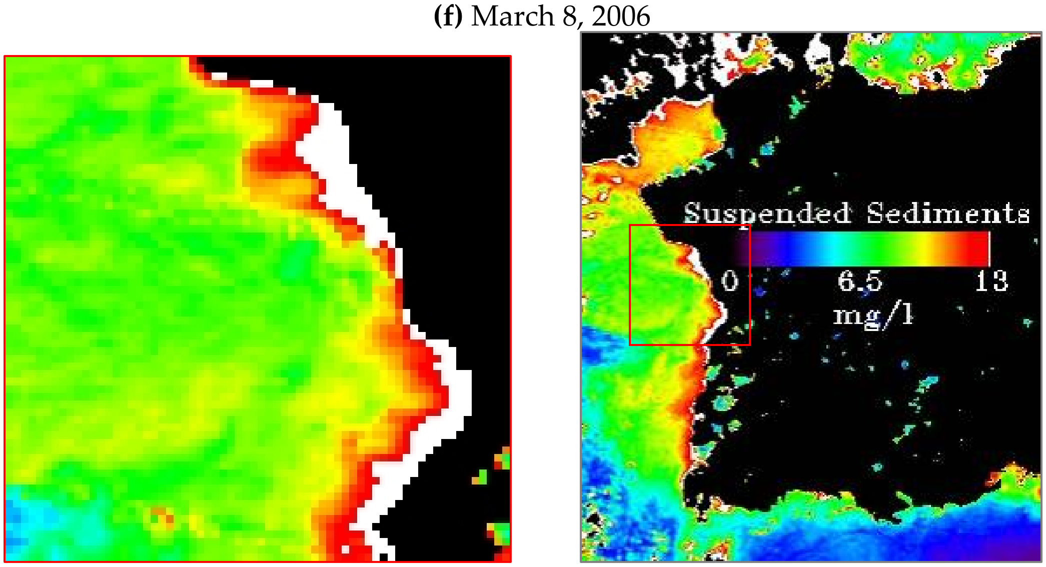


Figure 6. SS concentration estimations

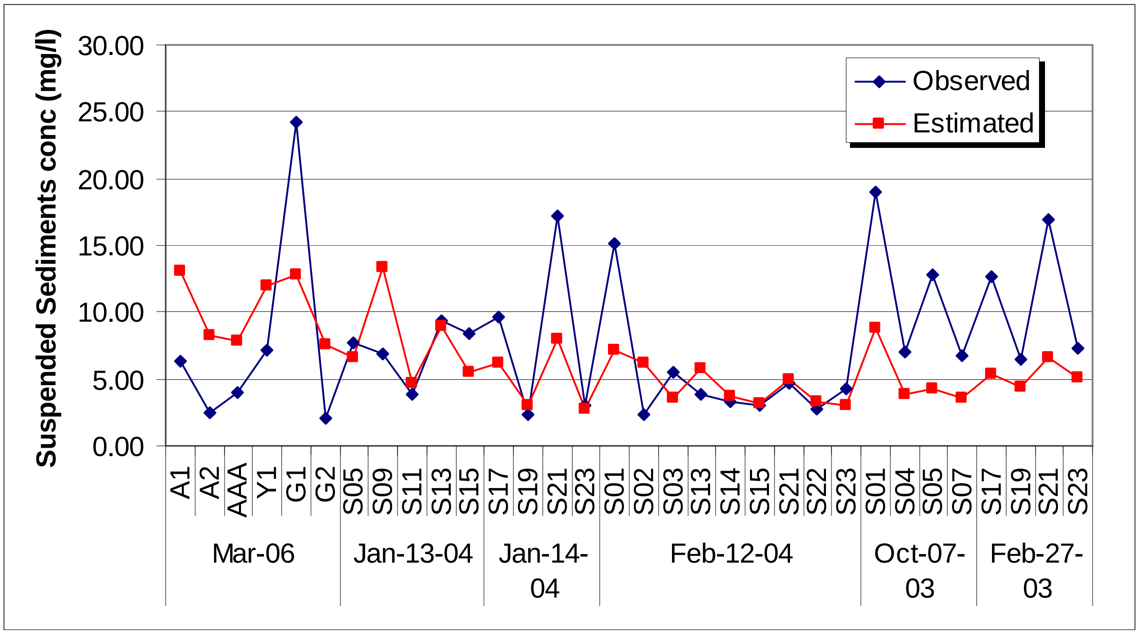


Figure 7. Comparison of algorithm estimated values and in situ measurements

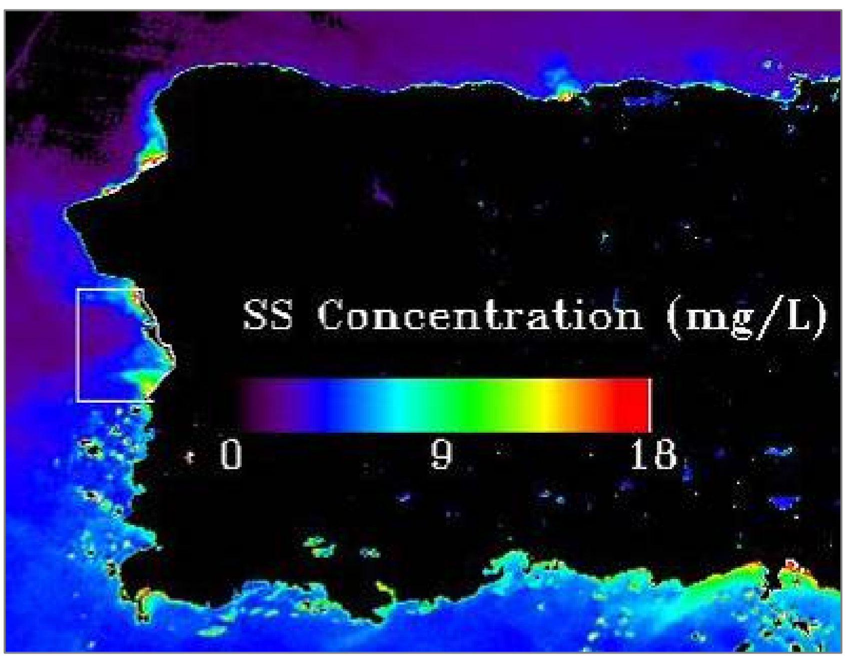


Figure 8. SS conc associated to a significant rain event

Data corrections of the AC 9 field spectrophotometer in Mayagüez Bay
Ramon Lopez

The in-situ spectrophotometer AC9 determines the spectral transmittance and spectral absorption of water over nine wavelengths and it has provided versatility to the study of ocean optics by taken traditional laboratory measurements such as absorption and attenuation measurements to in situ. Therefore this instrument has become an invaluable tool in the assessment of the inherent optical properties of marine environments. However when optical analysis are taken to the filed environment environmental factors have to be taken in consideration. For instance instrument drift has to be addressed by a field water calibration. The field water calibration directly before or after an in-water measurement will thus serve as the effective blank.

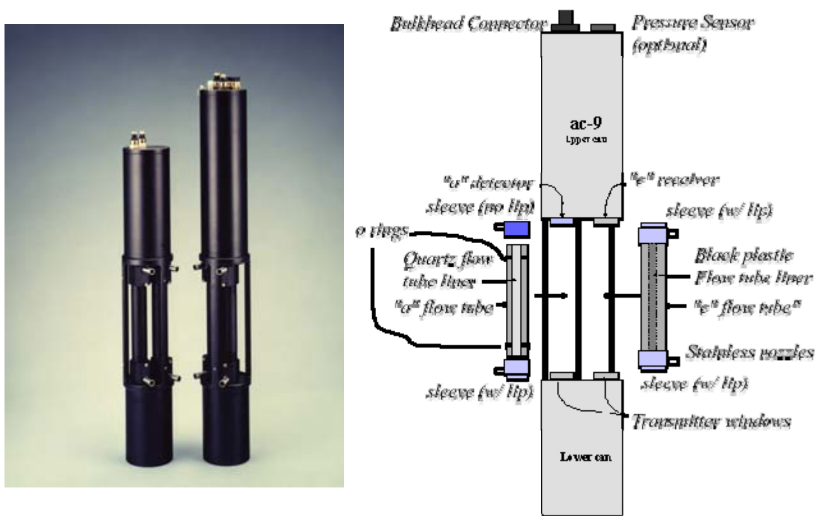


Figure 1 Left :AC-9 Spectrophotometer. Diagram on the right shows sampling chambers, a quartz reflective for absorption measurements and black plastic inner tube for attenuation measurements.

Another factor to take in consideration is the temperature and the dependence of absorption and attenuation on it. When calibrated the instrument response is analyzed by exposing the instrument to various samples of reference pure water of varying temperatures. Thus when used in the field the instruments is not only at a constant temperature the medium is sampling is of varying temperature and salinity, requiring post processing of the sampled data to correct for the deviations caused by these changeable environmental conditions. Pegau et al., 1997 developed a model to address the dependence of temperature and salinity in the absorption and attenuation of the light at the visible and infrared portion of the spectra. Such model is been used widely by the ocean optics community to adjust field measured data by AC-9 spectrophotometers. In this model the goela was to determine if there was a linear temperature slope (**(phi TSW** and salinity slope (**phiSC)** so that the absorption and attenuation coefficients of water can be given :

$$\text{c\_corr(L)} = \text{c(L)} - (\text{phi TSW(L)} * (\text{T\_meas} - \text{T\_cal}) + \text{phiSC(L)} * (\text{Sal\_meas});$$

$$\text{a\_corr(L)} = \text{a(L)} - (\text{phi TSW(L)} * (\text{T\_meas} - \text{T\_cal}) + \text{phiSA(L)} * (\text{Sal\_meas});$$

Where c(L) and a(L) are the measured attenuation and absorption and T_meas and T_cal are the measured and calibration temperatures and Sal_meas is the measured salinity.

Scattering correction is another adjustment typically apply to AC-9 data to compensate for the over estimation of the absorption coefficient due to scattering losses. Once temperature and salinity corrections are applied a none zero absorption signal is observed at 715 nm, due to the fact that particulate and dissolved materials exhibit negligible absorption in this region this signal is attributed to scattering loses out of the reflecting tube (Roesler, 1998). In conventional approaches with bench spectrophotometers the signal in the region of 715 is deduct from the rest of the spectra, subtracting equal portions to the spectra, hence it is named flat correction. Scattering coefficients are not spectrally flat and subtraction of the 715 nm from the entire measured absorption spectrum will not accurately correct the absorption coefficient. To remove the effect of scattering a spectral correction is calculated as a fraction of the spectral scattering coefficient. Characteristically the scattering coefficient is underestimated $b(\lambda) = c_{TS}(\lambda) - a_{TS}(\lambda)$, when part of the scattered signal is attributed to absorption in the reflecting tube. This error is removed by accounting the spectral variations in the scattering coefficient. The spectrally corrected absorption coefficient is then obtained by

$$a(\lambda) = a_{TS}(\lambda) - b(\lambda) +* \frac{a_{TS}(715)}{b(715)}$$

where $a_{TS}(\lambda)$ is the measured absorption coefficient with the salinity and temperature corrections applied, $a_{TS}(715)$ the absorption at 715, $b(\lambda)$ the scattering coefficient and $b(715)$ the scattering at 715 nm.

The Remote Sensing of Coastal Waters group over the years of the project has acquired a data set of inherent optical properties of the Mayaguez Bay. This data set includes a AC-9 spectrophotometer data that has been acquired over diverse environmental conditions due to the nature of the dynamics of the Mayaguez bay. This bay is subject to the influence of various river discharges therefore is characterized by different temperature and salinities regimes. For that reason this data set is been subject to the previously discussed corrections. For the water blank correction the factory temperature specific corrections is been applied according to the temperature of the instrument recorded temperature during each cast.

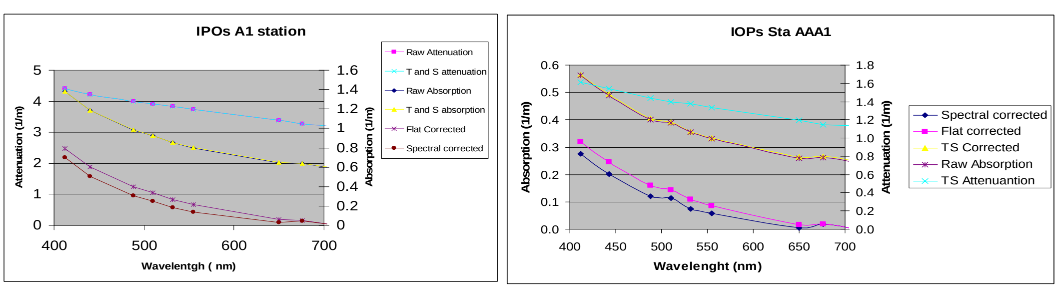


Figure 2. Data sample of the Añasco station 1 during October 2005 and Triple A station during September 2005 subjected to temperature-salinity corrections, and scattering corrections to absorption (flat and spectral corrected).

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MODIS Validation for Water Quality Parameters in Mayaguez Bay

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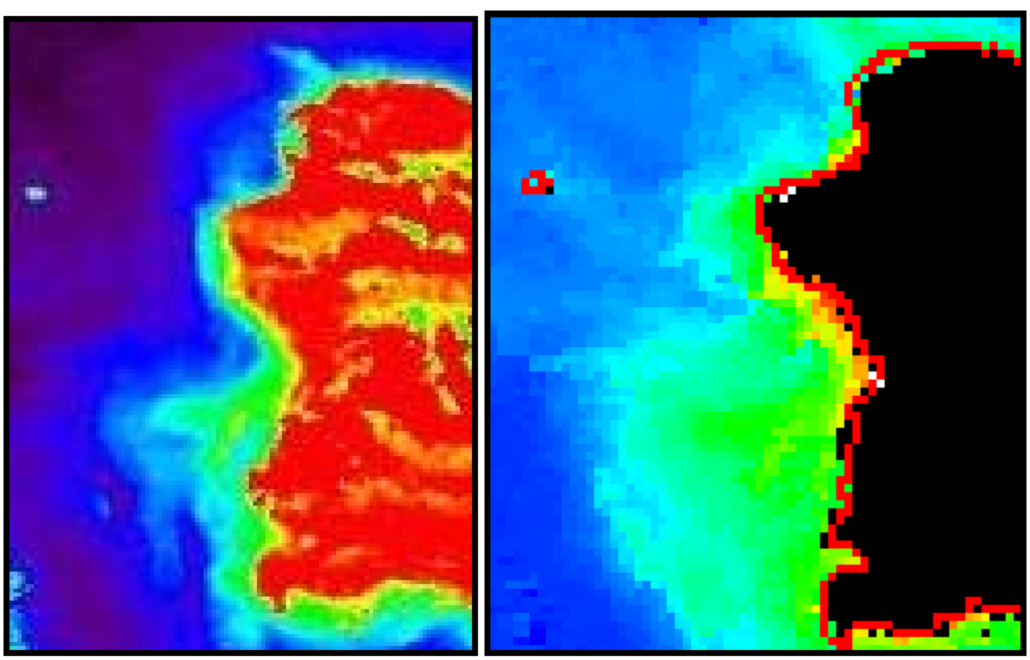
The Moderate Resolution Imaging Spectroradiometer (MODIS) is considered an improved generation of ocean color sensors. However, its validation for coastal monitoring is still underway. The main objective of this research was to validate the accuracy of MODIS to measure phytoplankton Chlorophyll-a (Chl-a) and suspended sediments (SS) in Mayagüez Bay, Puerto Rico. Field measurements of Chl-a and SS were compared with those estimated from MODIS data. A low correlation was found between field and MODIS Chl-a values obtained with both, Terra (R^2=0.0283) and Aqua (R^2=0.0265), satellites and using the standard NASA OC3 algorithm. Since the standard Chl-a product provided by NASA routines was not good for our study area, it was decided to derive and test a local empirical algorithm using MODIS Bands 3 (469 nm) and 4 (555 nm), which provide 500 meter of spatial resolution. The regressed linear equation for B3/B4 ratio and field Chl-a was $y = -0.6614x + 1.4937$ and the $R^2 = 0.3886$; while the logarithmic equation was $y = -0.4939Ln(x) + 0.7243$ and the $R^2 = 0.3688$. In order to estimate SS with MODIS, Band 1 (645 nm) with 250 meter of spatial resolution was used to validate the algorithm developed by Miller and McKee (2004) in the Gulf of Mexico. However, the suggested equation failed in Mayagüez Bay. A second approach intended to develop a site-specific algorithm for SS using this same band, but low correlation was also found on various testing scenarios. They were $R^2 = 0.1443$ (overall), $R^2 = 0.0695$ (dry season), $R^2 = 0.2788$ (rainy season), $R^2 = 0.0473$ (inshore stations), and $R^2 = 0.0468$ (offshore stations). Image processing and analyses clearly demonstrated that MODIS is not the most appropriate ocean color sensor for Mayagüez Bay. Another sensor with better temporal, spatial, and spectral resolutions is still needed for the estimation of Chl-a and SS in coastal waters.



Left: Image generated with new algorithm for Chl-a
Right: Image generated with NASA OC-3 algorithm for Chl-a

COASTAL –GILBES' GROUP REPORT

(Performance period: March 1, 2008 to August 31, 2008)

RESEARCH COMPONENT

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):**
  -Journal Publications with Students: Vilmaliz Rodriguez is now working with a journal publication that will be submitted to Remote Sensing of Environment before the end of the year.
  -On-line Publications: Hernández Guevara, Natlee M. (2008) Grain Size, Composition and Spectral Response of Deposited Sediments in Mayagüez Bay, 18 pages. (http://gers.uprm.edu/pdfs/topico_natlee2.pdf)
  -Books: PI and students have continued working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.
- **Dollar amount of funds leveraged with CREST funds (during performance period):**
  1. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
  2. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $25,000
- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None

- **Students PhD:** Patrick Reyes and Ramón Lopez, UPRM-Department of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** Nathlee Hernández, UPRM-Department of Geology (this student worked in a NOAA CREST related topic as part of the course Geol 40455, undergraduate research; but she was not directly funded)
- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences).
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Processing of field data collected in Mayaguez Bay over the past seven years was continued. The first version of a site-specific algorithm for the estimation of Total Suspended Sediments have been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. Several algorithms developed by different groups to estimate Chl-a using ocean color sensors were tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data. Good progress has been obtained in all proposed tasks.

Tasks (For year I as per the Milestone Chart)

Task (1) Compare to satellite water leaving products and atmosphere retrievals

Interactions among the bio-optically active components found in Mayagüez Bay were studied using Hydrolight 4.2. Dominance of the inorganic mineral particles on the spectral shape and magnitude of the remote sensing reflectance was evident when mineral concentrations where over 5 mg/l and chlorophyll a concentrations between 0.1 and 1 micrograms/liter. This information was used to develop and validate ocean color algorithms for the estimation of chlorophyll a in Mayagüez Bay. Two of the three empirical algorithms developed for the bay perform better than the 14 published algorithms tested. Due to the complex optical nature of coastal waters, alternative methods for the remote estimation of primary production may be needed in sediment rich systems.

Task (2) Intercomparison of the below/above water signals with aircraft and satellite data as available.

Use of satellite derived data for TSS estimation is Mayagüez Bay was investigated in order to provide more resources for costal monitoring. Understanding of the dynamics and association between apparent and inherent optical properties is necessary for the development of this type of algorithms, especially in optically complex waters. We used *in situ* measurements of total suspended sediments (TSS), backscattering and R_{rs} to examine and define the relationship between these parameters for inferring of TSS concentrations using ocean color sensors. Good relationships resulted from TSS concentration and b_{bp} linear regression analyses in all six wavelengths (R^2=0.74-0.76; n=133; P<0.0001 for all cases). Resultant regressions, between b_b and R_{rs} using corresponding wavelength, show significant wavelength dependant variations where best relationship was observed at 620 nm. The analysis of R_{rs} single band and R_{rs} ratio for derivation of TSS indicates that red to green ratio ($R_{rs}655/R_{rs}545$) present the best correlation results (R^2=0.84; n=72). Simultaneous MODIS reflectance band 1 data and *in situ* measurements of TSS concentration, b_{bp} 620 and $R_{rs}645$ were all positively correlated.

Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):**
  -Journal Publications with Students: Vilmaliz Rodriguez is now working with a journal publication that will be submitted to Remote Sensing of Environment before the end of the year.
  -On-line Publications: Hernández Guevara, Natlee M. (2008) Grain Size, Composition and Spectral Response of Deposited Sediments in Mayagüez Bay, 18 pages. (http://gers.uprm.edu/pdfs/topico_natlee2.pdf)
  -Books: PI and students have continued working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.
- **Dollar amount of funds leveraged with CREST funds (during performance period):**

1. Study of Benthic Habitats Using Hyperspectral Remote Sensing. Sponsored by NSF-Center for Subsurface Sensing and Imagine Systems (CenSSIS). $25,000
2. Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands. Sponsored by the Puerto Rico Sea Grant. $25,000

- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Patrick Reyes and Ramón Lopez, UPRM-Department of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** Nathlee Hernández, UPRM-Department of Geology (this student worked in a NOAA CREST related topic as part of the course Geol 40455, undergraduate research; but she was not directly funded)
- **NOAA Collaborators:** Richard Stumpf from the NOAA's National Centers for Coastal Ocean Science (NCCOS). He is an expert in the application of remote sensing to coastal waters, especially for the estimation of suspended sediments and Chl-a.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), Richard Miller (National Aeronautics and Space Administration), and Roy Armstrong (UPRM-Department of Marine Sciences).
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Processing of field data collected in Mayaguez Bay over the past seven years was continued. The first version of a site-specific algorithm for the estimation of Total Suspended Sediments have been developed and tested, although further testing and tuning is necessary. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. Several algorithms developed by different groups to estimate Chl-a using ocean color sensors were tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data. Bio-optical data collected during the past six years with a rosette have been incorporated in a GIS-database for further analyses and comparisons with satellite data. Good progress has been obtained in all proposed tasks.

Tasks (For year II as per the Milestone Chart)

Task (7) Analysis of optical field measurement together with Chl, TSS concentrations

Use of satellite derived data for TSS estimation is Mayagüez Bay was investigated in order to provide more resources for costal monitoring. Understanding of the dynamics and association between apparent and inherent optical properties is necessary for the development of this type of algorithms, especially in optically complex waters. We used *in situ* measurements of total suspended sediments (TSS), backscattering and R_{rs} to examine and define the relationship between these parameters for inferring of TSS concentrations using ocean color sensors. Good relationships resulted from TSS concentration and b_{bp} linear regression analyses in all six wavelengths (R^2=0.74-0.76; n=133; P<0.0001 for all cases). Resultant regressions, between b_b and R_{rs} using corresponding wavelength, show significant wavelength dependant variations where best relationship was observed at 620 nm. The analysis of R_{rs} single band and R_{rs} ratio for derivation of TSS indicates that red to green ratio ($R_{rs}655/R_{rs}545$) present the best correlation results (R^2=0.84; n=72). Simultaneous MODIS reflectance band 1 data and *in situ* measurements of TSS concentration, b_{bp} 620 and $R_{rs}645$ were all positively correlated.

Task (8) Evolution and tuning of algorithm for Chl retrieval in PR coastal waters

Interactions among the bio-optically active components found in Mayagüez Bay were studied using Hydrolight 4.2. Dominance of the inorganic mineral particles on the spectral shape and magnitude of the remote sensing reflectance was evident when mineral concentrations where over 5 mg/l and chlorophyll a concentrations between 0.1 and 1 micrograms/liter. This information was used to develop and validate ocean color algorithms for the estimation of chlorophyll a in Mayagüez Bay. Two of the three empirical algorithms developed for the bay perform better than the 14 published algorithms tested. Due to the complex optical nature of coastal waters, alternative methods for the remote estimation of primary production may be needed in sediment rich systems.

Task (9) Development of GIS database for land sea interactions in Mayaguez Bay

All data collected in Mayaguez Bay was put to the process of quality control in which all the different sets were corrected and calibrated according to the specification of every instrument and method. Once calibrated it was organized into excel spreadsheets according to the sampled stations during the cruises. From these data sets a series of parameters were chosen to be converted into a GIS project to make possible the analysis of the dynamics of the bay. The selected parameters include the inherent optical properties, suspended sediments, chlorophyll and salinity. The sampled stations were used to create interpolated layers using the spatial analyst Spline function in ArcGIS. Once the parameters were chosen and organize into layers, additional ancillary data was added to the projects to facilitate the analysis. This new ancillary data includes benthic types, bathymetry, watersheds and river and streams, roads, and geology of Mayaguez area. These ArcMap projects then were published in the web using ArcIMS. The data cruises already available are February and October of 2003 and March, April, September, and October of 2006. The web address is http://gersview.uprm.edu/mayabay.html.

Future Tasks (From the Milestones)

Efforts for developing site-specific algorithms for Chlorophyll-a and suspended sediments will continue. Other sampled months are being organized and they are getting ready for the GIS databases. Very soon they will be exported to ArcIMS and be published in the web. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay. Ramón Lopez, will continue working with this important aspect of the project. A publication by Vilmaliz Rodriguez will be submitted to the Remote Sensing of Environment journal before the end of the year. The PI and other students will continue working with the chapters of the Mayaguez Bay book.

Use of remote sensing reflectance, backscattering and MODIS data to estimate total suspended sediments in Mayagüez bay

Vilmaliz Rodríguez-Guzmán & Fernando Gilbes-Santaella

Abstract

Use of satellite derived data for TSS estimation is Mayagüez bay is investigated in order to provide more resources for costal monitoring. Understanding of the dynamics and association between apparent and inherent optical properties is necessary for the development of this type of algorithms, especially in optically complex waters. We used in situ measurements of total suspended sediments (TSS), backscattering and R_{rs} to examine and define the relationship between these parameters for inferring of TSS concentrations. Good relationships resulted from TSS concentration and b_{bp} linear regression analyses in all six wavelengths (R^2=0.74-0.76; n=133; P<0.0001 for all cases). Resultant regressions, between b_b and R_{rs} using corresponding wavelength, show significant wavelength dependant variations where best relationship was observed at 620 nm. The analysis of R_{rs} single band and R_{rs} ratio for derivation of TSS indicates that red to green ratio ($R_{rs}655/R_{rs}545$) present the best correlation results (R^2=0.84; n=72). Simultaneous MODIS reflectance band 1 data and in situ measurements of TSS concentration, b_{bp} 620 and $R_{rs}645$ were all positively correlated, but more data is require to better define and validate resultant relations.

Introduction

Comprehension of relationships between water constituents, inherent optical properties (IOPs) and apparent optical properties (AOPs) is important for characterizing the marine optical environment, developing remote sensing ocean color algorithms (D'Sa and Miller, 2003) and interpretation of satellite imagery for coastal case 2 waters (Doxaran et al., 2002a). Empirical relationships will be calculated incorporating measurements of TSS concentration, optical backscattering, in-situ remote sensing reflectance (R_{rs}) and MODIS data in order to provide a baseline for the development of site specific algorithms to estimate TSS in Mayagüez bay. Scattering is a fundamental process in light propagation in the ocean, where electromagnetic radiation is deflected from its original beam by particles. The optical backscattering coefficient (b_b) indicates, in units of m^{-1}, the attenuation caused by scattering at angles from 90° to 180°. Considering that this coefficient is representative of the amount of photons scattered backward, it is directly related to reflectance information collected near the water surface or even ocean waters data obtained from satellite sensors (Dana and Maffione, 2002; Boss et al., 2004a). The are many constituents in water that affects the b_b coefficient such as bubbles, organic and inorganic particles, Colloids, liquid or oil particles, an extensive description of the role and significance of each one of these constituents to b_b are discussed in Stramski, et al., 2004. Additionally, better understanding of this parameter will provide valuable information necessary to interpret and analyze satellite information considering that in ocean waters satellite sensors essentially recorded images of backscattered light (Dana and Maffione, 2002; Boss et al., 2004b).

Numerous studies have used measurements collected from satellite sensors to detect spatial variations of water quality parameters associated to TSS concentrations (Ritchie et al., 1976; Miller et al., 1994; Otero et al., 1992; Doxaran et al. 2002a; Binding et al., 2003; Chen and Muller-Karger, 2007). MODIS appears to be a suitable sensor for the purposes of this study because the data is very accessible, it contains two 250m resolution bands at 645 nm (band 1) and 859nm (band 2) which are in a spectral region typically associated to TSS concentration (Athius, 1998; Doxaran et al. 2003), and finally this sensor has a very fine temporal resolution (one day) that provides information for daily monitoring. Previous studies have validated MODIS band 1 (620-670 nm; 250 m) to estimate concentration of TSS (Miller and McKee, 2004). However, unsatisfactory results are obtained when these algorithms are applied in Mayagüez Bay. Some of the limitations encountered during the process were: (i) the small spatial extensions of the study area (95 Km^2); (ii) the abundance of TSS and other water constituents in this bay are relatively low compared to characteristic conditions of case 2 waters; (iii) specific optical properties for this area were not considered. These factors make necessary the development of site-specific algorithms to retrieve product of water quality parameters (e.g. TSS) through remote (Menon et al., 2005) or in situ optical measurements.

Main objective of this study is to derive relationships between TSS, backscasttering, above water remote sensing reflectance and satellite measurements in order to develop algorithms for TSS concentration estimation.

Methods

The study period encompasses twelve research cruises that were carried out between January 2004 and October 2006 (See table 1). A total of 17 stations were monitored within this period for bio-optical properties, remote sensing reflectance (R_{rs}) and laboratory measurements of TSS, chl-a and C-DOM (Fig. 1). From these stations, six are permanent and eleven were visited only in special missions during the first year of the study period (2004). Distribution of stations along the bay aims to detect variations associated to river discharge by aligning them in transects that extent from the mouths of the Añasco, Yagüez and Guanajibo rivers. Eleven additional sites at the river mouths were monitored for R_{rs} and TSS during three days of sampling (June 4, 11 and 16 May) Parameters incorporated and discussed within this report are TSS concentration, backscattering coefficients (b_b & b_{bp}) and R_{rs}.

For TSS concentration measurements, duplicated water samples were taken at each station at the surface and in deep water. The water was filtered thought Millipore ® HA 0.45 µm white nylon HNWP 47mm diameter membrane. These filters were previously oven-dried over-night at 60ºC and pre-weighed in and analytical balance ±.0001g. The filtered water volumes varied between station samples (depending on the sediment load of each sample). The filters were then dried at 60ºC over-night and then re-weighted.

Vertical profiles of total backscattering (b_b) and particle backscattering (b_{bp}) at six different wavelengths (442, 470, 510, 579, 620 & 671/675 nm) were measured using a HydroScat-6 (HS-6, elaborated by HOBI Labs). This instrument converts a raw signal to a value of Volume Scattering Function (VSF) around a single fixed angle of 140º (Maffione & Dana, 1997). From these values and other defaults calibration coefficients estimations of b_b and b_{bp} were made using HOBI-Labs processing software (HydroSoft). All raw-files collected during the entire study period were processed using the same version of HydroSoft (v.274) to ensure consistency in the data set (D. Dana, personal communication, 2008). Finally, full resolution vertical profiles were used to generate binned profiles of b_b and b_{bp} with a 0.5 m resolution.

Above water remote sensing reflectance (R_{rs}) was calculated for each station with a GER 1500 (Geophysical and Environmental Research) 512-channel portable spectroradiometer following SeaWiFS protocols (Mueller and Austin, 1995). The resulting scan data was then plotted for quality control evaluation and any curve with anomalies (e.g. clouds, sun glint, boat shadow) was not included in the dataset. Subsequently, mean values were calculated for each parameter and then used to calculate R_{rs} by the following equation:

$$R_{rs}(\lambda) = \frac{L_0(\lambda) - f\,(L_s(\lambda))}{E_d(0^+, \lambda)} \qquad (1)$$

Where $L_0(\lambda)$ is the total radiance of the sea surface, $L_s(\lambda)$ is sky radiance, $E_d(0^+, \lambda)$ is down welling irradiance and f is the Fresnell coefficient (0.028 at 45°). The curves were corrected by subtracting the minimum measured value between 900-920 nm, in a few cases the curves were corrected by even lower regions (730-900 nm) (suggested by Lee, personal communication).

Images corresponding to the dates of the research cruises were downloaded through a NASA Internet server called Landweb. The product selected was MOD02QKM (calibrated radiances level L1b at 250 m), which contains reflectance and radiance data for MODIS band 1 (620-670 nm) and 2 (841-876 nm). Following downloading the data, images were displayed to verify their quality and then processed using ENVI v. 3.4. This software provided all tools necessary for pre-processing and analysis. All images were spatially subset for Puerto Rico region including surrounding coastal and oceanic waters, and georeferenced as UTM Zone19N NAD83. The georeferentiation was validated by overlaying seventeen points corresponding to shoreline limits within the Mayagüez Bay on a georeferenced band 2 image to determine their proximity to the shoreline and detect possible displacements. The spectral region of this band (841-876 nm) causes high absorption in water whereas land is highly reflective producing a sharp contrast between land and water that allows better recognition of the shoreline. Subsequent to georeferentiation, an atmospheric correction was applied using a pre-defined routine named *dark substract*. A point vector file with stations location and ID information was overlaid to the images and, then reflectance associated to those locations were exported as an ASCII file using exporting options of the ROI (Region of Interest) tool. Images were evaluated to ensure that all extracted reflectance values were from clouds free pixels.

Results and Discussion

Relationship between b_{bp}, TSS and R_{rs}

Inter-relationships between b_{bp}, TSS and R_{rs} were defined based on six wavelengths: 442, 47, 510, 589, 620 and 675 (Table 2). Good relationships resulted from TSS concentration and b_{bp} linear regression analyses in all six wavelengths (R^2=0.74-0.76; n=133; P<0.0001 for all cases). Similarity in correlations results in b_b and b_{bp} indicates that TSS dominates the backscattered signal in all six wavelengths. Although there are not major differences between correlation results between bands, coefficients of determinations (R^2) tended to increase with longer wavelengths. Nearly identical regression results were obtained doing same analysis with b_b coefficient, with a slightly decrease in coefficients of determinations for all wavelengths (results not presented here). The best correlation between TSS and b_{bp} is observed at 675 nm (R^2=0.76), however this channel is highly affected by chl-a fluorescence (McKee and Cunningham, 2006; Huot et al, 2007) and it will not be consider for TSS estimation. The second better explained regression was obtained at 620 nm (R^2=0.75; n=133; P<0.001), which represents a good channel to estimate TSS considering that typically sediments have a high response in this region of the electromagnetic spectrum. Figure2 shows three examples with data and linear regression defined for 442, 510 and 620 nm channels. It was noticed that the three points located farther to the linear fit all correspond to station I6, indicating that this station is contributing a high amount of the variability observed in this analysis.

All six channels surface measurements (0.5 m) of b_b were correlated with respective wavelengths of in-situ R_{rs} in order to determine how detection of backscattering varies within the visible region of the electromagnetic spectrum. Resultant regressions show significant wavelength dependant variations where square correlation coefficients increased with longer wavelengths (Fig. 3). Best correlation was observed at 620 nm (R^2=0.78; n=61), follows by 589 nm (R^2=0.77; n=61) and 675 nm (R^2=0.67; n=61) all with a significance P value <0.0001. In the red region pure water has an important contribution to total absorption, therefore variations detected in R_{rs} are mainly influenced by total backscattering (Tzortziou et al., 2007). For shorter wavelengths, values of R_{rs} shows major variability not observed in b_b measurements that results in not significant relationships in 442 nm, 470 nm and 510 nm (R^2= 0.14, R^2=0.24, R^2= 0.54, respectively; n=61). Tzortziou et al. (2007), explains that in shorter wavelengths, R_{rs} is affected by both, total backscattering of suspended particles and absorption by non-covarying particles and dissolved components due to the minimal contribution of pure water absorption. Based on this asseveration, resultant poor correlations in short wavelengths suggest not only the influence of both parameters but the dominance of absorption over backscattering.

Effect of TSS on remote sensing reflectance

For the following analysis eleven measurements carried out at the river mouths (June 2008) were incorporated in order to have more values representative of high TSS concentration. Remote sensing reflectance curves were plotted using all collected data and calculating mean values of R_{rs} associated to four different ranges of TSS concentrations. Variations in magnitude and spectral shape are observed among four different ranges of TSS concentration (<5 mg/l, 6-10 mg/l, 11-20 mg/l and > 20 mg/l) (Fig. 4). Detectable increase in R_{rs} magnitude is observed from 550 nm to 800 nm with higher concentrations of TSS. A significant peak is observed in the near-infrared region (775nm to 825nm) when concentrations are more than 20 mg/l, this signal is lost in lower concentrations suggesting a direct association of TSS and R_{rs} response in this region. These results are similar to obtained in previous studies (Ritchie et al., 1976; Doxaran et al., 2002a; Doxaran et al., 2003) even when TSS concentrations are significantly lower than normally used in this type of analysis. In highly turbid waters this relation can be successfully used to incorporate near-infrared wavelengths to develop algorithms for TSS estimations (Doxaran et al., 2002a; Moore et al., 1999), for Mayagüez Bay the signal in this region is too weak for satellite data validation considering the dominance of waters with relatively low concentration conditions, additionally, water leaving radiance will not be strong enough to mitigate the effect of the atmospheric backscatter in the signal.

Correlations between TSS and a wide range of R_{rs} parameters of single and spectral band ratios were established combining data from research cruises and from sampling made at the river mouths (Table 3). We examined correlation results at same wavelengths presented in previous analysis (442*, 470, 510*, 589, 620*, 675 nm) (Fig. 5) to facilitate the integration of all results, and at various wavebands and ratios associated to spectral characteristics of satellite sensors such as MODIS, SeaWiFS and MERIS to define and propose colour ratios for remotely sensed data applications. Within the single band analysis, best correlations were observed in the red region with a significant good relationship (R^2 = 0.73; n=72) for all 589, 620 and 645 nm bands. In longer wavelengths (665 and 675 nm) determination coefficients decrease slightly until it reaches the near-infrared region where a poor correlation is observed at 859 nm (R^2=0.46; n=72); both 645 and 859 nm wavelengths represent the center of MODIS band 1 and 2, respectively.

Considering that the use of colour ratios reduces the variability of reflectance associated to changes in particle characteristics (e.g. size and shape) (Doxaran et al., 2002b, Moore et al., 1999), this approach was included in the analysis in order to compare ratios and single band correlations results. It was determined that coefficient of determination increased when using colour ratios. Wernand (1998) evaluated colour ratios associated to SeaWiFS band 1 (412 nm) and 6 (670 nm) and MERIS bands 5 (560 nm) and 6 (620 nm) for TSS estimation with reasonable results. Same ratios were incorporated in our analysis establishing significant exponential relationships with TSS (R^2= 0.75 for $R_{rs}560/R_{rs}620$ and R^2=0.77 for $R_{rs}412/R_{rs}670$). Our analysis presented a stronger correlation using same ratio with R_{rs} (R^2=0.81; n=72) than when use simple R_{rs} in red (e.g. R_{rs} 665; R^2=0.71; n=72). These results differ to observed by Binding et al. (2005) where the correlation between mineral suspended sediments and red to green ratios was weak

(R^2=0.65), compared to a the strong coefficient of determination (R^2=0.92) resulted by using a single band at 665 nm. After evaluating various combinations within the visible spectral region, it was determined that best relationship was observed when correlating red:green ratio specifically at 655 and 545 nm (R^2=0.84; n=72) (Fig. 6). Better relationship between red to green reflectance ratios suggest that mineral suspended sediment dominates water optical properties, over the effect of phytoplankton and yellow substances (Binding et al, 2003). This reduces the influence of these water constituents in water leaving radiance, presenting an advantage for the development of algorithms to estimate TSS from satellite derived data in Mayagüez bay.

Comparison between MODIS data and in situ measurements

Agreement between the reflectance measured from a satellite sensor and in situ measurements was evaluated by using MODIS reflectance band 1 measurements and research cruises data. The in situ parameters included in this analysis were TSS concentration, b_{bp} at 620 nm and R_{rs} at 645 nm. These two bands were used because previous results indicated that 620 nm represents a potential wavelength for TSS estimation and 645 nm is the center wavelength of MODIS band 1. It was determined that the relationship between TSS and MODIS band 1 reflectance is poor, only 43 percent of the variance was explained with the defined equation (TSS=195.62 * MODIS band 1 + 0.2552; R^2= 0.43; n=34) (Fig. 7a). A better coefficient of determination was observed, but statistically weak, when using b_{bp} at 620 nm (R^2=0.52; n=48; $P<0.0001$)(Fig.7b). Two relationships were defined between R_{rs} 645 (MODIS band 1 center) and MODIS reflectance because of the presence of an outlier in the dataset (Fig. 7c). This outlier corresponds to station I1 sampled during a high discharge event occurred in August 17, 2005; it was identified as significant because the mean discharge for that day was equal to 2,200 cubft/sec, while the mean discharge for the month of August is 411 cubfts (calculation period: Oct-01-1985 to Sept-30-2006) (USGS, 2008). The correlation results when incorporating this point shows a strong relationship (R^2=0.88; n=30; $P<0.0001$) between these two parameters, indicating a correspondence between MODIS reflectance and in situ measurements. A decrease in both, slope and square correlation coefficient (R^2=0.69; n=29; $p< 0.0001$), is observed when that point is eliminated. Although this can be considered more statistically valid the inclusion of that point in the analysis can give a better idea of the tendency of the relationship. This value is considered an extreme value representative of rare but real conditions, more sampling associated to high river discharge is necessary to reinforce correlation defined. Poor correlations between MODIS reflectance and is situ data can be attribute to factors such as, high spatial variability, atmosphere effect, sensors and in situ measurement errors, difference in timing between in situ measurements and satellite overpasses (Chang et al., 2006).

Conclusions

TSS dominate backscattered signal in all six wavelengths evaluated, which are all distributed along the visible region of the electromagnetic spectrum. However, the relationship between b_b and R_{rs} indicates that the best channel to be used for TSS estimation is 620 nm, because it is where total backscattering dominates absorption in R_{rs} measurements, different to shorter wavelengths where R_{rs} is dominated by absorption of non-covarying particles and dissolved components. Results showed good correlations between TSS and R_{rs} single band analysis in the red region, and better results are obtained with the incorporation of red to green ratios indicating dominance of TSS in Mayagüez bay optical properties. Comparison between MODIS band 1 reflectance and b_{bp} 620nm and TSS in situ measurements presented poor correlations, while a strong correlation between R_{rs} and MODIS was defined. The main limitation of this analysis was MODIS data unavailability due to high percent of cloud covered in most of the cruises dates. More data is needed to reinforce and validate the relationships.

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Appendix: Tables and Figures

Table 1: Cruises details

Dates	Season	No. of stations	Fiel Data missing	MODIS data (useful)
January 12-14, 2004	Dry	12		X (two images)
February 12, 2004	Dry	9	TSS Depth; R_{rs}	X
August 19, 2004	Dry	10	TSS Depth	
July 19, 2005	Rainy	6	TSS Depth	
August 17, 2005	Rainy	5	TSS Depth	X
September 20, 2005	Rainy	6		
October 19, 2005	Rainy	6		X
December 6, 2005	Dry	6		X
March 8, 2006	Dry	5	R_{rs}	X
April 21, 2006	Dry	5		
September 26, 2006	Rainy	6		
October 26, 2006	Rainy	6		

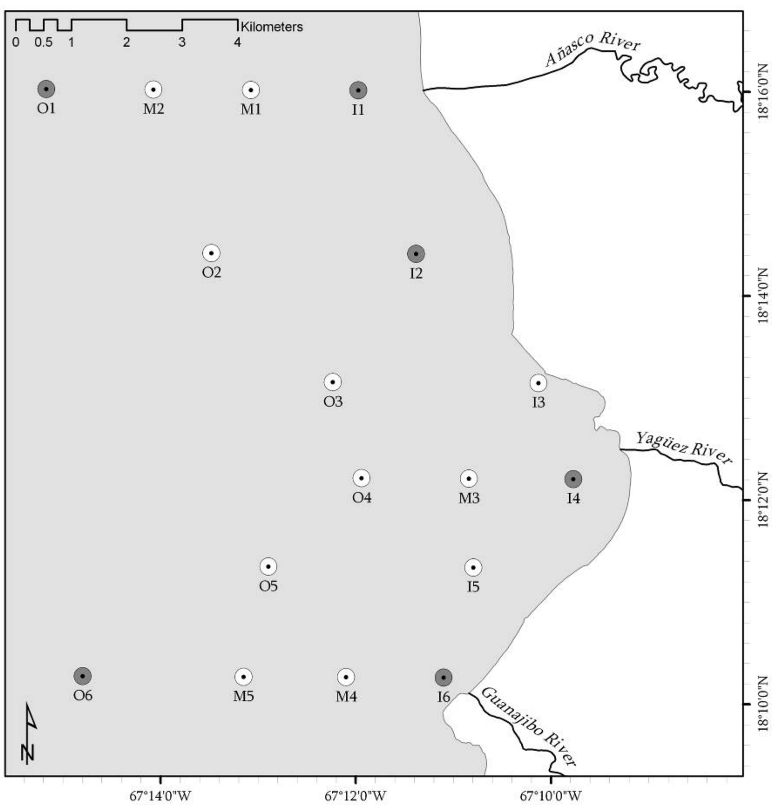


Figure 1: The Mayagüez Bay with seventeen stations monitored within the study period (January 2004 to October 2006). Stations colored in white indicate specific sites that were sampled only during special missions, while six stations in gray are permanent stations. Letter assigned to station ID refers to the location in terms of their distance to the shoreline (inshore-I, middle-M and offshore-O)

Table 2: Regression relationships between TSS, backscattering and R_{rs} in Mayagüez Bay

wavelength (λ)	Regression relationship; n=133; TSS =	R^2	Regression relationship; n=61; $R_{rs}(\lambda)$ =	R^2
442	70.616 * (b_{bp}442) + 2.1996	0.74	0.0157 * (b_b442) + 0.0062	0.14
470	81.786 * (b_{bp}470) + 2.3444	0.74	0.0272 * (b_b470) + 0.0073	0.24
510	71.632 * (b_{bp}510) + 2.4213	0.73	0.0593 * (b_b510) + 0.0075	0.54
589	59.066 * (b_{bp}589) + 2.6036	0.74	0.1337 * (b_b589) + 0.0022	0.77
620	64.895 * (b_{bp}620) + 2.5188	0.75	0.1415 * (b_b620) + 5E-06	0.78
675	79.089 * (b_{bp}675) + 2.391	0.76	0.1356 * (b_b675) - 0.0008	0.67

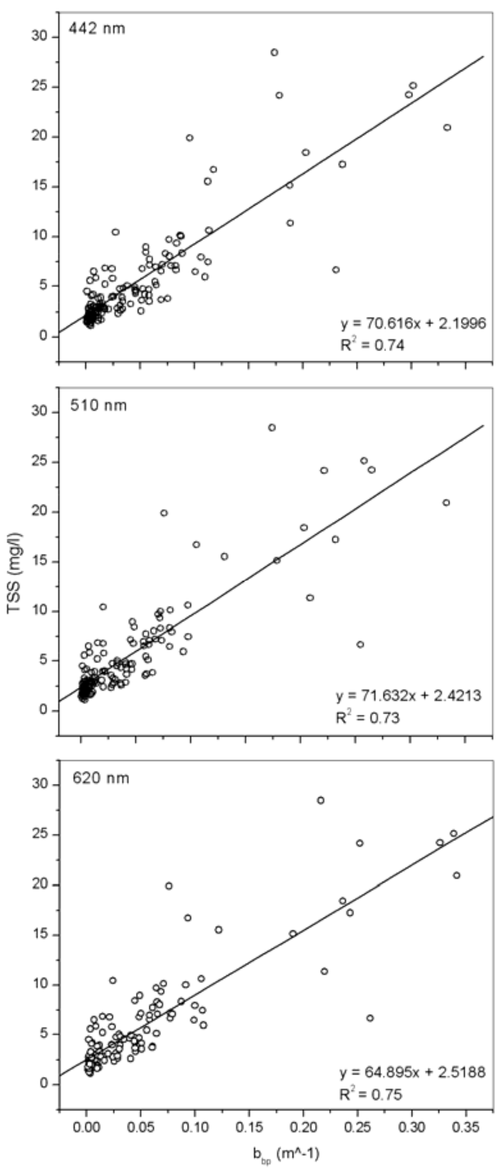


Figure 2. Relationship between bbp (m^-1) and TSS concentration (mg/l)

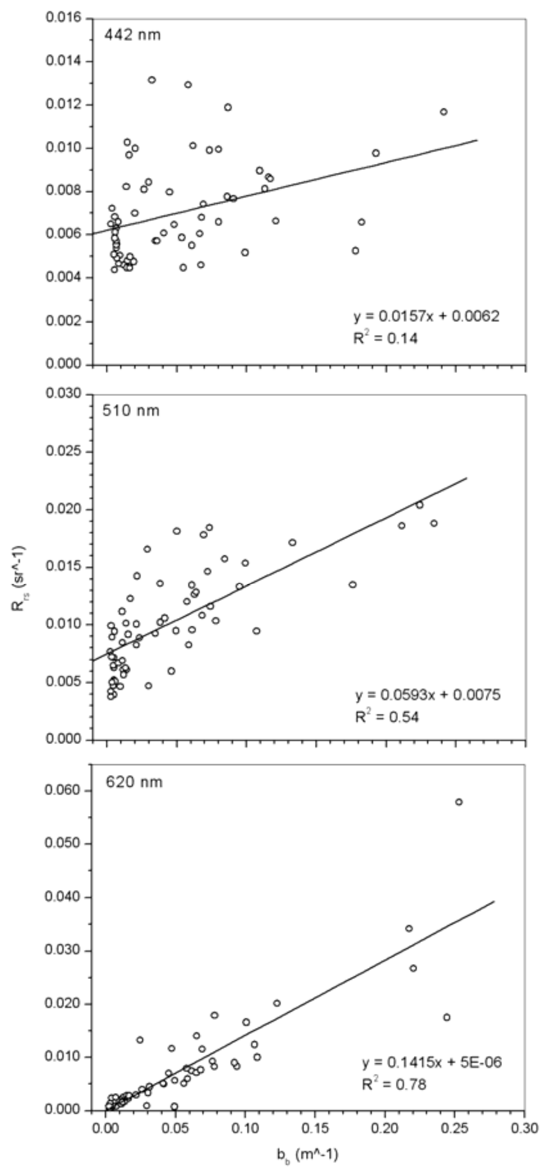


Figure 3. Relationship between bb (m^-1) and Rrs (sr^-1)

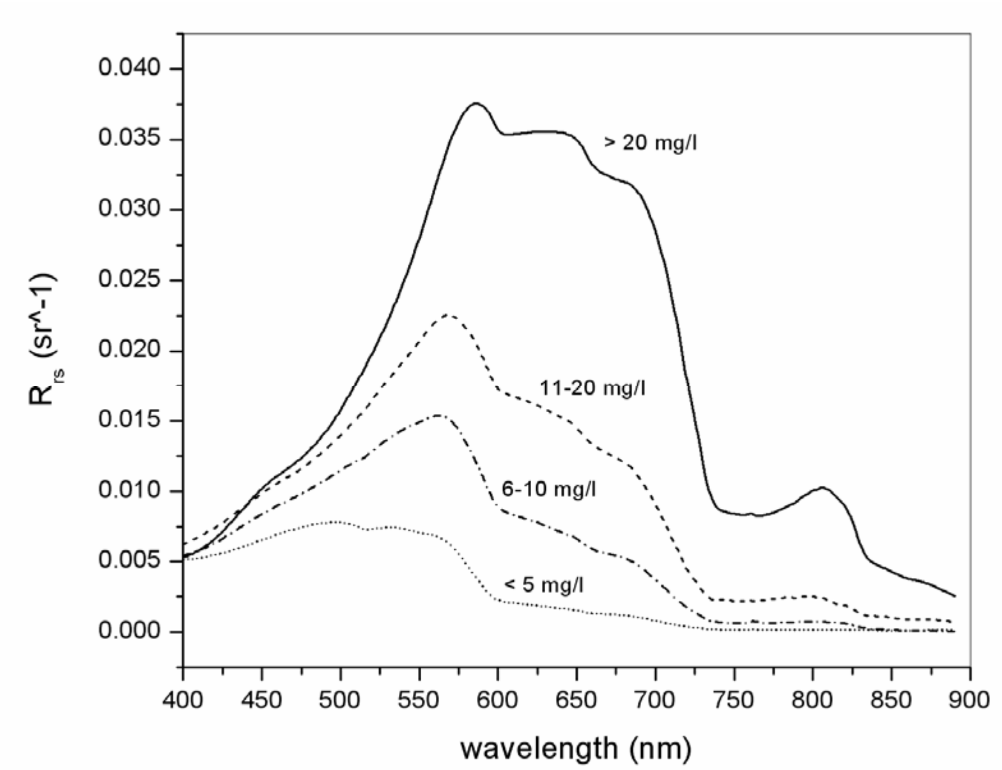


Figure 4. Average Rrs spectrum for 4 concentration ranges if TSS in Mayagüez Bay. by using mean measured in-situ R_{rs} and associated TSS concentration for all the study period (January 2004 to June 2008)

Table 3: Regression relationships between TSS concentration and different reflectance parameters

R_{rs} parameter (X)	Regression relationship; n=72; TSS =	R^2
$R_{rs}(442)$	1357.9 * (X) - 1.512	0.17
$R_{rs}(470)$	1331.6 * (X) - 3.4123	0.24
$R_{rs}(510)$	1153.2 * (X) - 4.2096	0.45
$R_{rs}(589)$	579.58 * (X) + 1.6079	0.73
$R_{rs}(620)$	599.3 * (X) + 2.7821	0.73
$R_{rs}(645)$	602.63 * (X) + 3.1481	0.73
$R_{rs}(665)$	634.34 * (X) + 3.5357	0.71
$R_{rs}(675)$	641.76 * (X) + 3.6363	0.71
$R_{rs}(859)$	3675.4 * (X) + 5.9588	0.46
$R_{rs}(560)/R_{rs}(620)$	$16.941 * (X)^{-1.232}$	0.75
$R_{rs}(412)/R_{rs}(670)$	$7.7701 * (X)^{-0.5628}$	0.77
$R_{rs}(665)/R_{rs}(555)$	23.943 * (X) - 0.7366	0.81
$R_{rs}(655)/R_{rs}(545)$	20.353 * (X) - 0.3937	0.84

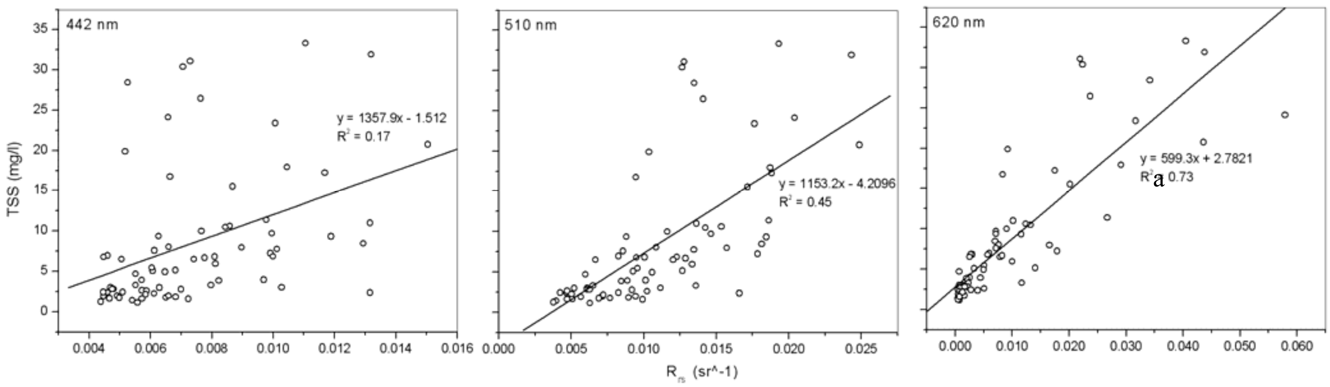


Figure 5. Relationship between TSS concentration (mg/l) and R_{rs} at three wavelengths (442, 510 and 620 nm)

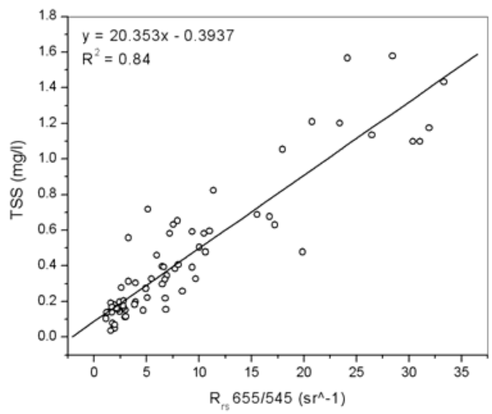


Figure 6. Relationshibetween TSS concentration (mg/l) and Rrs 655/645 (sr^-1)

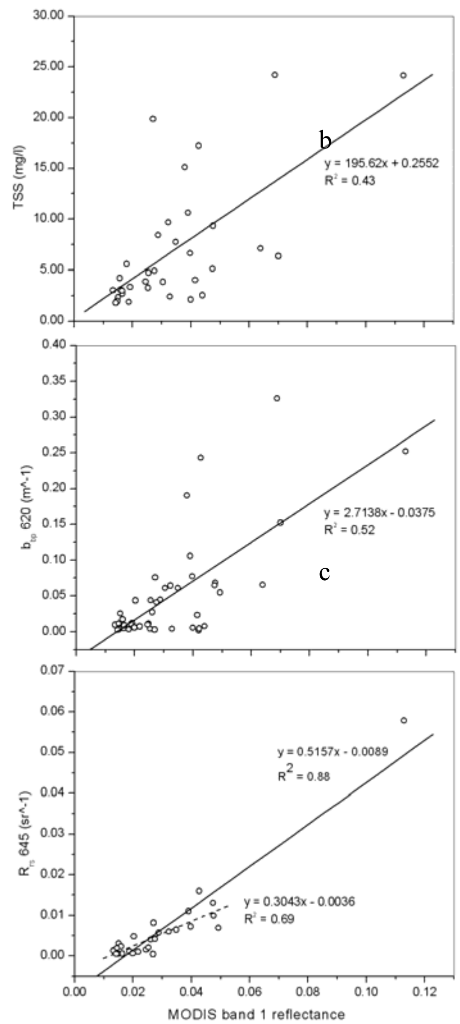


Figure 7. Relationship between MODIS band 1 reflectance and in situ measurements

Site-Specific Algorithm for the Estimation of Chlorophyll-a in Mayaguez Bay

Marcos A. Rosado
Ph.D. Candidate, Department of Marine Sciences

Abstract-Interactions among the bio-optically active components found in Mayagüez Bay were studied using Hydrolight 4.2. Dominance of the inorganic mineral particles on the spectral shape and magnitude of the remote sensing reflectance was evident when mineral concentrations where over 5 mg/l and chlorophyll a concentrations between 0.1 and 1 micrograms/liter. This information was used to develop and validate ocean color algorithms for the estimation of chlorophyll a in Mayagüez Bay. Two of the three empirical algorithms developed for the bay perform better than the 14 published algorithms tested. Due to the complex optical nature of coastal waters, alternative methods for the remote estimation of primary production may be needed in sediment rich systems.

Mayagüez Bay is located in western Puerto Rico and presents a unique opportunity as a marine bio-optics natural laboratory. The bay is characterized by a complex environment, influenced by river discharge and anthropogenic activities. The goals of the project are to better understand how optically active constituents of case-2 waters interact in the bay and to developed ocean color algorithms based on that knowledge.

The first part of the project was assessing the power of a commercially available bio-optical numerical analysis package (Hydrolight 4.2) to predict the remote sensing reflectance curve based on a four component model. The model components are: water, chlorophyll *a* (Chl *a*), colored dissolved organic matter (CDOM) and inorganic minerals. Some of the results of the validation are shown in Figure 1.

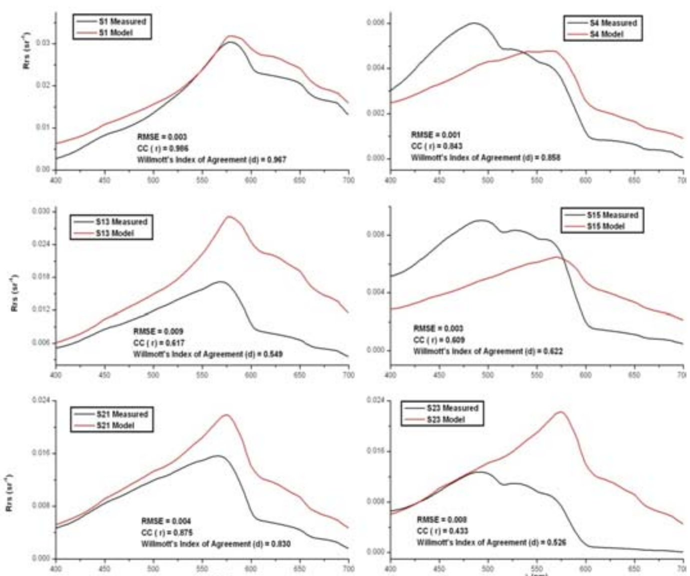


Figure 1. October 2001 Hydrolight Rrs (0+, λ) validation results for selected stations in Mayagüez Bay.

The second part of the project was to simulate the Rrs (λ) using Hydrolight 4.2. Chl *a* , CDOM and mineral particles concentrations were varied in order to simulate the variety of conditions found in Mayagüez Bay. Figure 2 show some of the results obtained.

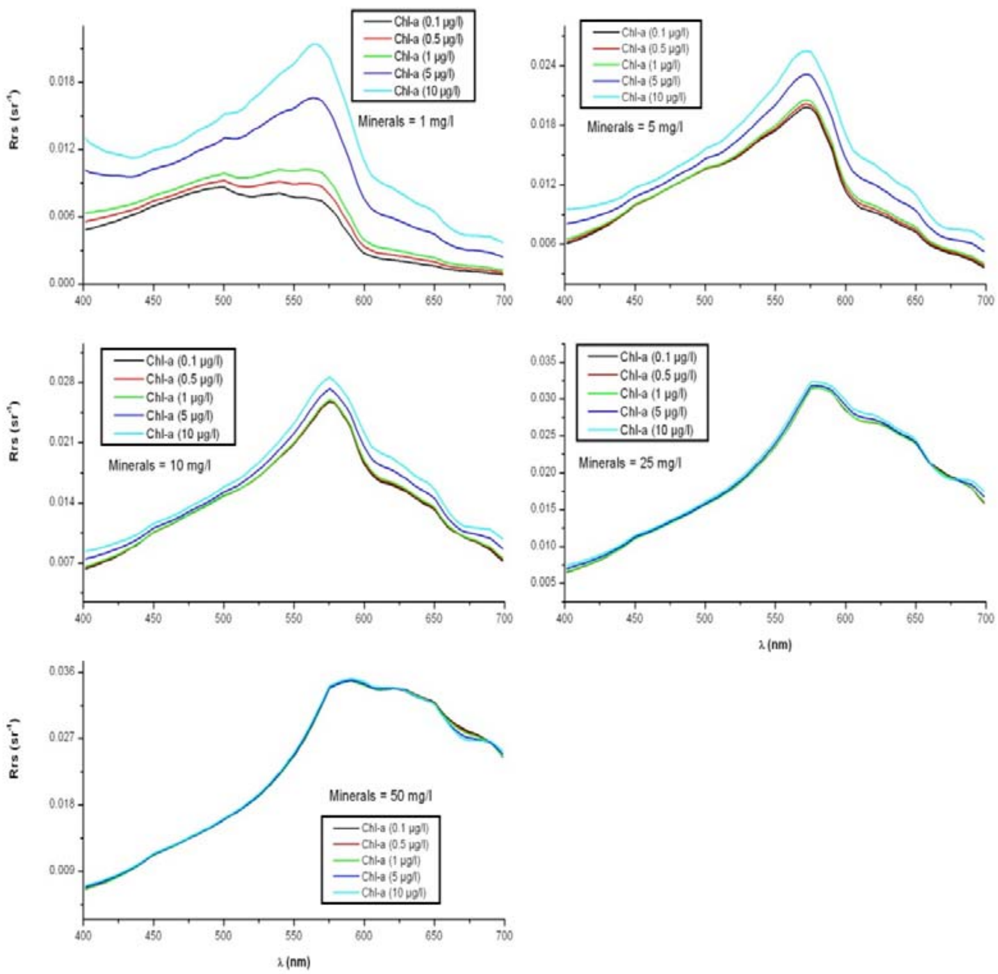


Figure 2. ***Rrs curves modeled by Hydrolight when CDOM absorption was set at 0.05 m^{-1} at 443 nm. Graphs represent 1, 5, 10, 25 and 50 mg/l of red clay minerals.***

An interesting finding was that when mineral concentrations were above 5 mg/l, there is no dependence between Chl *a* and the Rrs curve, especially in the 0.1 – 1 μg/l Chl *a* range. This fact is very important for the process of algorithm development and validation for the bay.

The second part of my research deals with algorithm evaluation and development. The performance of 14 empirical ocean color algorithms and a quasi-analytical algorithm (QAA) was assessed for both the complete data set and for the TSS < 5 mg/l subset. Some of the results are presented in figure 3.

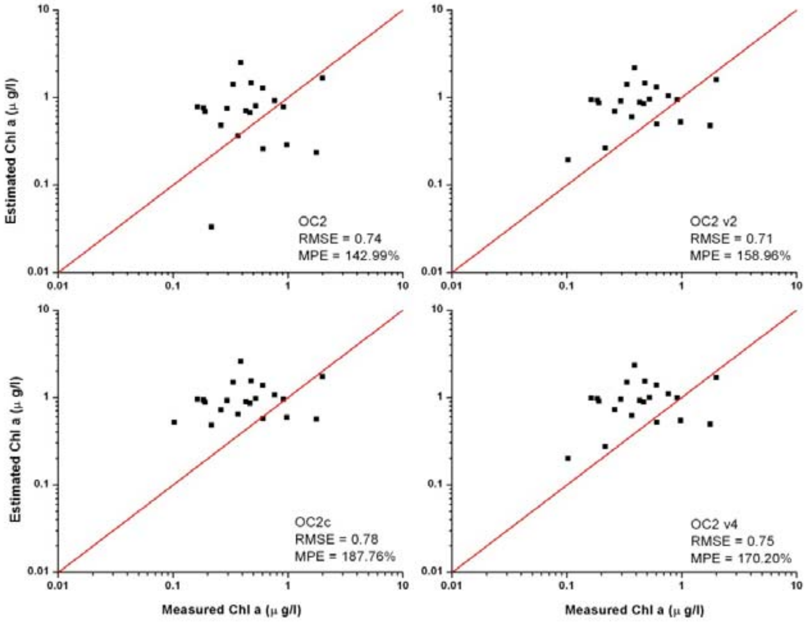


Figure 3. Chl a estimated by OC2, OC2 v2, OC2c and OC2 v4 empirical algorithms versus measured Chl a for the data set TSS < 5 mg/l.

Using the results from the algorithm evaluation, three algorithms were developed for the Mayagüez Bay TSS < 5 mg/l data set. Two of the band algorithms were based on the Rrs 490/Rrs 555 ratio and the third was based on the Rrs 670/Rrs 680 ratio. The curve fitting was done using the Origin 7.0 Scientific Analysis Software. The result of the quadratic model fitting is shown in Figure 4.

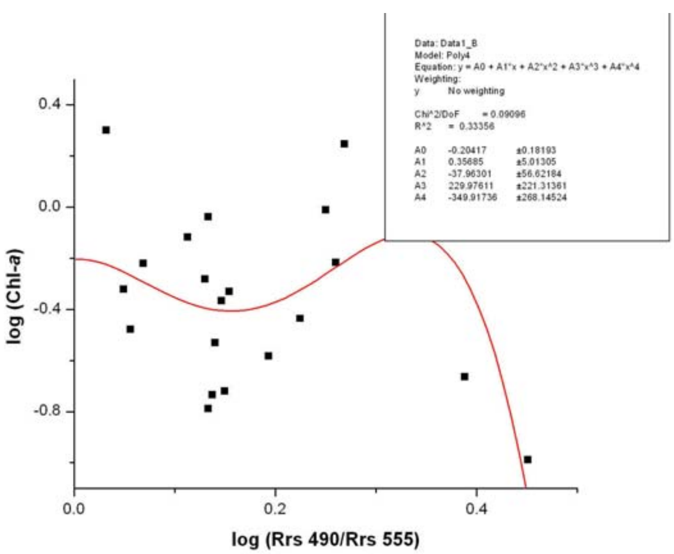


Figure 4. Fourth order polynomial curve fitting of the log (Chl a) versus log (Rrs 490/Rrs 455). The model equation is log(Chl a) = -0.20417 + 0.35685 log(Rrs 490/ Rrs 455) – 37.96301 log(Rrs 490/ Rrs 455)^2 + 229.97611 log(Rrs 490/ Rrs 455)^3 - 349.91736 log(Rrs 490/ Rrs 455)^4.

The algorithms reduced the root mean squared error (RMSE) and the mean percent error (MPE) by approximately 73% compared with the best performing published algorithms tested.

Figure 5 shows the correspondence between estimated and measured Chl *a* for the quadratic algorithm.

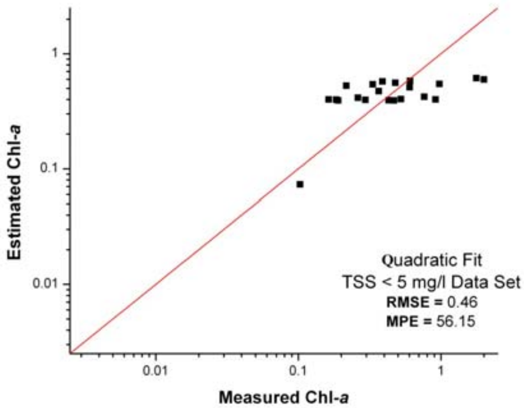


Figure 5. Performance of the quadratic fit algorithm developed with the TSS < 5 mg/l data set. RMSE was reduced to 0.46 and MPE was reduced to 56.15% in comparison with the previously tested algorithms.

The algorithms were then tested with a data set different that the one used in their development. The validation data set consisted of Chl *a* and Rrs (λ) measurements taken in the bay in cruises carried out from 2004 to 2006. The best performing of the developed relationships was the Rrs 670/Rrs 680 algorithm (RMSE = 0.48, MPE = 79.0%), followed by the quadratic algorithm (RMSE = 0.58, MPE = 120.15%). The results for the quadratic algorithm validation are shown in Figure 6.

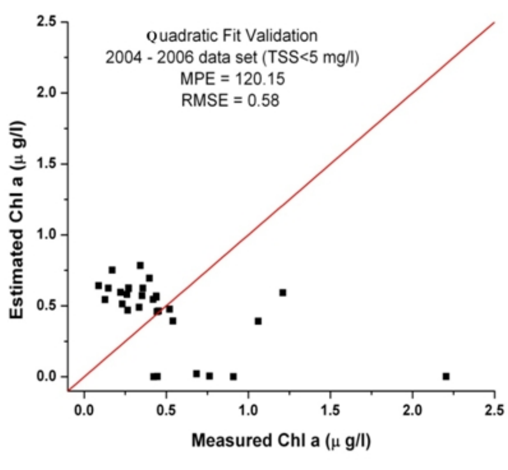


Figure 6. Quadratic algorithm performance when validated using new data (2004 – 2006 cruises, TSS < 5mg/l). Note that RMSE and MPE are smaller than those obtained with the 14 algorithms tested.

In summary, inorganic red clay minerals dominate the Rrs(λ) at the Chl *a* concentrations commonly found in Mayagüez Bay. In order to accurately estimate Chl *a* using remote sensing, a better understanding of the inorganic particles dynamics is needed. Alternative approaches for primary production estimation may be necessary in environments with high suspended particle concentrations.

Development of the GERSVIEW Data portal

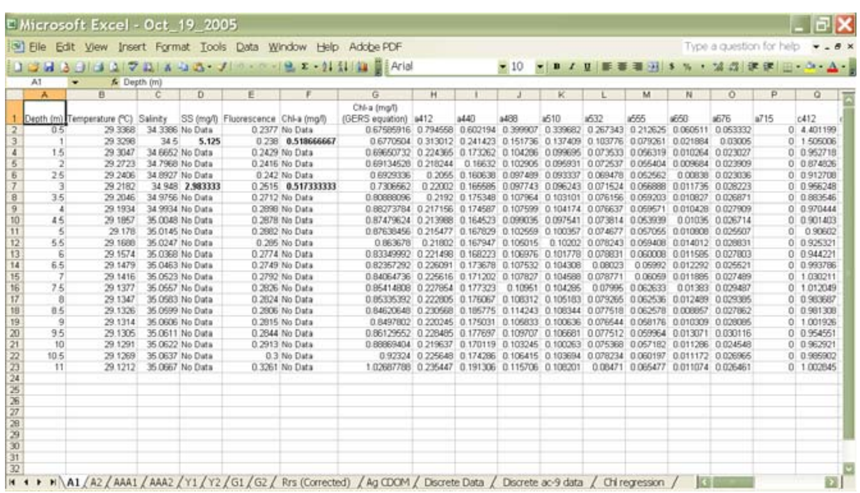
Ramon Lopez UPRM-Marine Sciences Department

The Remote Sensing of Coastal Waters group over the years of the project has acquired a data set that includes apparent and inherent optical properties and biogeochemical parameters of the Mayaguez Bay. This data set includes a AC-9 spectrophotometer data, suspended sediments, chlorophyll concentration, and CTD data, that has been acquired over diverse environmental conditions due to the nature of the dynamics of the Mayaguez bay. This bay is subject to the influence of various river discharges therefore is characterized by different temperature and salinities regimes. This data set corresponds to data that have been collected since 2001over 21 cruises to the bay (Table 1).

Table 1 Available data sets for the cruises to the Bay Mayaguez

Sampled Months										
Apr-01	Oct-01	Feb-02	Aug-02	Feb-03	Oct-03	Jan-04	Feb-04	Aug-04	Mar-05	Jul-05
Aug-05	Sep-05	Oct-05	Dec-05	Mar-06	Apr-06	Sep-06	Oct-06	May-07	Mar-08	

The data was put to the process of quality control in which all the different sets were corrected and calibrated according to the specification of every instrument and method. Once calibrated it was organized into excel spreadsheets according to the sampled stations during the cruises (Figure 1). The excel format was chosen because of it facility access and distribution. From these data sets a series of parameters were chosen to be converted into a GIS project to make possible the analysis of the dynamics of the bay. The selected parameters include the inherent optical properties, the suspended sediments, chlorophyll concentrations and the salinity variations of the bay. The sampled stations were used to create interpolated layers using a the spatial analyst Spline function. Interpolation predicts values for cells in a raster from a limited number of sample data points. It can be used to predict unknown values for any geographic point data, such as elevation, rainfall, chemical concentrations, noise levels, and so on. The Spline method is an interpolation method that estimates values using a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points. It fits a mathematical function to a specified number of nearest input points while passing through the sample points. This method is best for generating gently varying surfaces such as elevation, water table heights, and for instance the parameters sampled in our project.



Depth (m)	Temperature (°C)	Salinity	SS (mg/l)	Fluorescence	Chl-a (mg/l)	Chl-a (mg/l) (GERS equation)	a412	a440	a488	a510	a532	a555	a650	a676	a715	c412
0.5	29.3368	34.3386	No Data	0.2377	No Data	0.67585916	0.794558	0.602194	0.399907	0.339682	0.267343	0.212625	0.060511	0.053332	0	4.401199
1	29.3298	34.5	**5.125**	0.238	**0.518666667**	0.6770504	0.313012	0.241423	0.151736	0.137409	0.103776	0.079261	0.021884	0.03005	0	1.505006
1.5	29.3047	34.6652	No Data	0.2429	No Data	0.69650732	0.224365	0.173262	0.104286	0.099695	0.073533	0.056319	0.010264	0.023027	0	0.952718
2	29.2723	34.7968	No Data	0.2416	No Data	0.69134528	0.218244	0.16632	0.102905	0.095931	0.072537	0.055404	0.009684	0.023909	0	0.874826
2.5	29.2406	34.8927	No Data	0.242	No Data	0.6929336	0.2055	0.160638	0.097489	0.093337	0.069478	0.052562	0.00838	0.023036	0	0.912708
3	29.2182	34.948	**2.983333**	0.2515	**0.517333333**	0.7306662	0.22002	0.165585	0.097743	0.096243	0.071524	0.056888	0.011735	0.028223	0	0.956248
3.5	29.2046	34.9756	No Data	0.2712	No Data	0.80888096	0.2192	0.175348	0.107964	0.103101	0.076156	0.059203	0.010827	0.026871	0	0.883546
4	29.1934	34.9934	No Data	0.2898	No Data	0.88273784	0.217156	0.174587	0.107599	0.104174	0.076637	0.059571	0.010428	0.027909	0	0.970444
4.5	29.1857	35.0048	No Data	0.2878	No Data	0.87479624	0.213988	0.164523	0.099035	0.097541	0.073814	0.053939	0.01035	0.026714	0	0.901403
5	29.178	35.0145	No Data	0.2882	No Data	0.87638456	0.215477	0.167829	0.102559	0.100357	0.074677	0.057055	0.010808	0.025507	0	0.90602
5.5	29.1688	35.0247	No Data	0.285	No Data	0.863678	0.21802	0.167947	0.105015	0.10202	0.078243	0.059408	0.014012	0.028831	0	0.925321
6	29.1574	35.0368	No Data	0.2774	No Data	0.83349992	0.221498	0.168223	0.106976	0.101778	0.078831	0.060008	0.011585	0.027803	0	0.944221
6.5	29.1479	35.0463	No Data	0.2749	No Data	0.82357292	0.226091	0.173678	0.107532	0.104308	0.08023	0.05992	0.012292	0.025521	0	0.993786
7	29.1416	35.0523	No Data	0.2792	No Data	0.84064736	0.225616	0.171202	0.107827	0.104588	0.078771	0.06059	0.011885	0.027489	0	1.030211
7.5	29.1377	35.0557	No Data	0.2826	No Data	0.85414808	0.227854	0.177323	0.10951	0.104285	0.07995	0.062633	0.01383	0.029487	0	1.012049
8	29.1347	35.0583	No Data	0.2824	No Data	0.85335392	0.222805	0.176067	0.108312	0.105183	0.079265	0.062536	0.012489	0.029385	0	0.983687
8.5	29.1326	35.0599	No Data	0.2806	No Data	0.84620648	0.230568	0.185775	0.114243	0.108344	0.077518	0.062578	0.008857	0.027862	0	0.981308
9	29.1314	35.0606	No Data	0.2815	No Data	0.8497802	0.220245	0.175031	0.105833	0.100636	0.076544	0.058176	0.010309	0.028085	0	1.001926
9.5	29.1305	35.0611	No Data	0.2844	No Data	0.86129552	0.228485	0.177697	0.109707	0.106681	0.077512	0.059964	0.013071	0.030116	0	0.954551
10	29.1291	35.0622	No Data	0.2913	No Data	0.88869404	0.219637	0.170119	0.103245	0.100263	0.075368	0.057182	0.011286	0.024548	0	0.962921
10.5	29.1269	35.0637	No Data	0.3	No Data	0.92324	0.225648	0.174286	0.106415	0.103694	0.078234	0.060197	0.011172	0.026965	0	0.985902
11	29.1212	35.0667	No Data	0.3261	No Data	1.02687788	0.235447	0.191306	0.115706	0.108201	0.08471	0.065477	0.011074	0.026461	0	1.002845

Figure 1 Sample excel spreadsheet with the data organized according to stations and cruises for the Mayaguez bay project.

Once the parameters were chosen and organize into layers, additional ancillary data was added to the projects to facilitate the analysis. This new ancillary data includes the bays benthic types (coral reefs, sea grass bottoms etc..) , and the bathymetry of the bay, the extend of the different watershed and river and streams affecting the bay, the roads in the area, and geology of Mayaguez area.

To further facilitate the access to the sampled data, these ArcMap projects then were published to the web for the general public usage, using the Web Map Server ARCIMS. This map server provided the means to serve maps across the internet in a similar arrangement as it would by a GIS desktop tool. This allowed the layers of the Mayaguez bay to be overlapped and be related to the different ancillary parameters that were included in the ARCMAP project. Figure 3 shows a screen shot of one of the published pages. The web address to the portal is http://gersview.uprm.edu. Besides the user being able to visually analyze the layer interactions it will be possible to access the data that originated them.

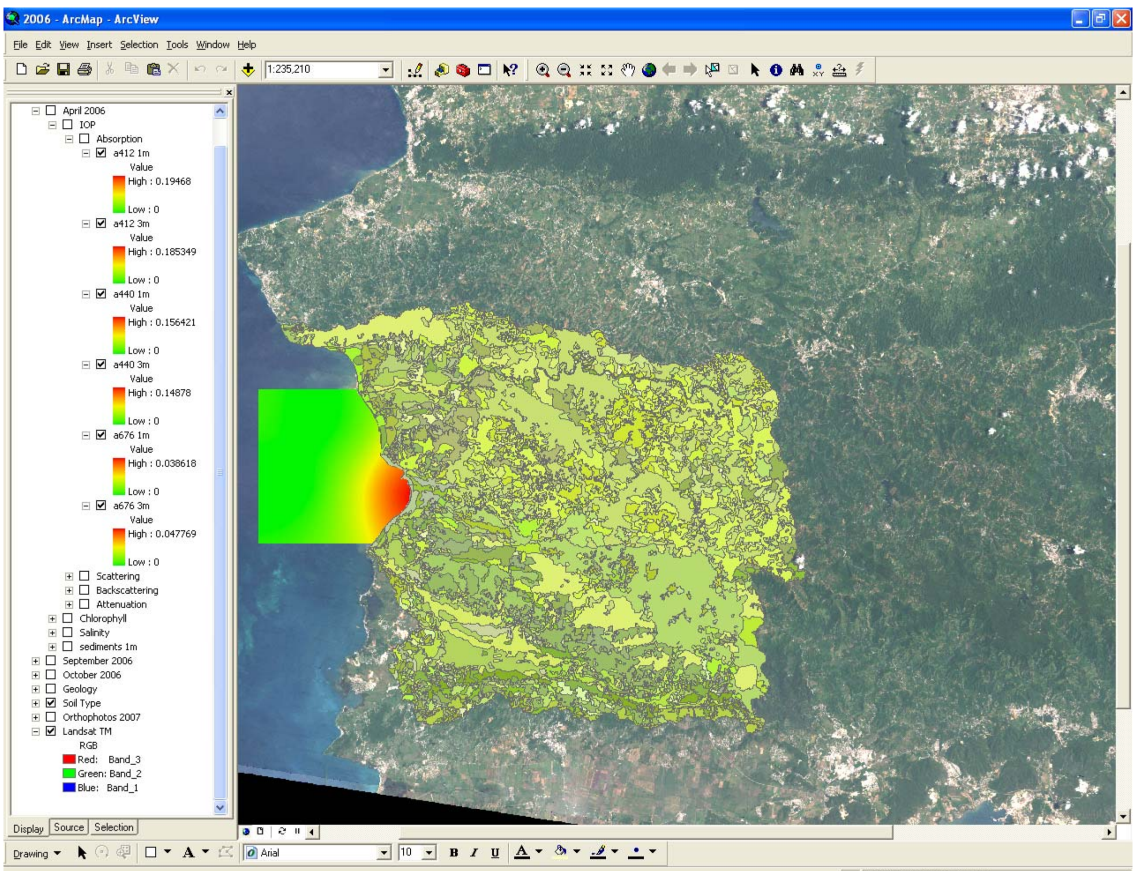


Figure 2 Sample ARCMAP project of selected parameters according to stations and cruises for the Mayaguez bay data set.

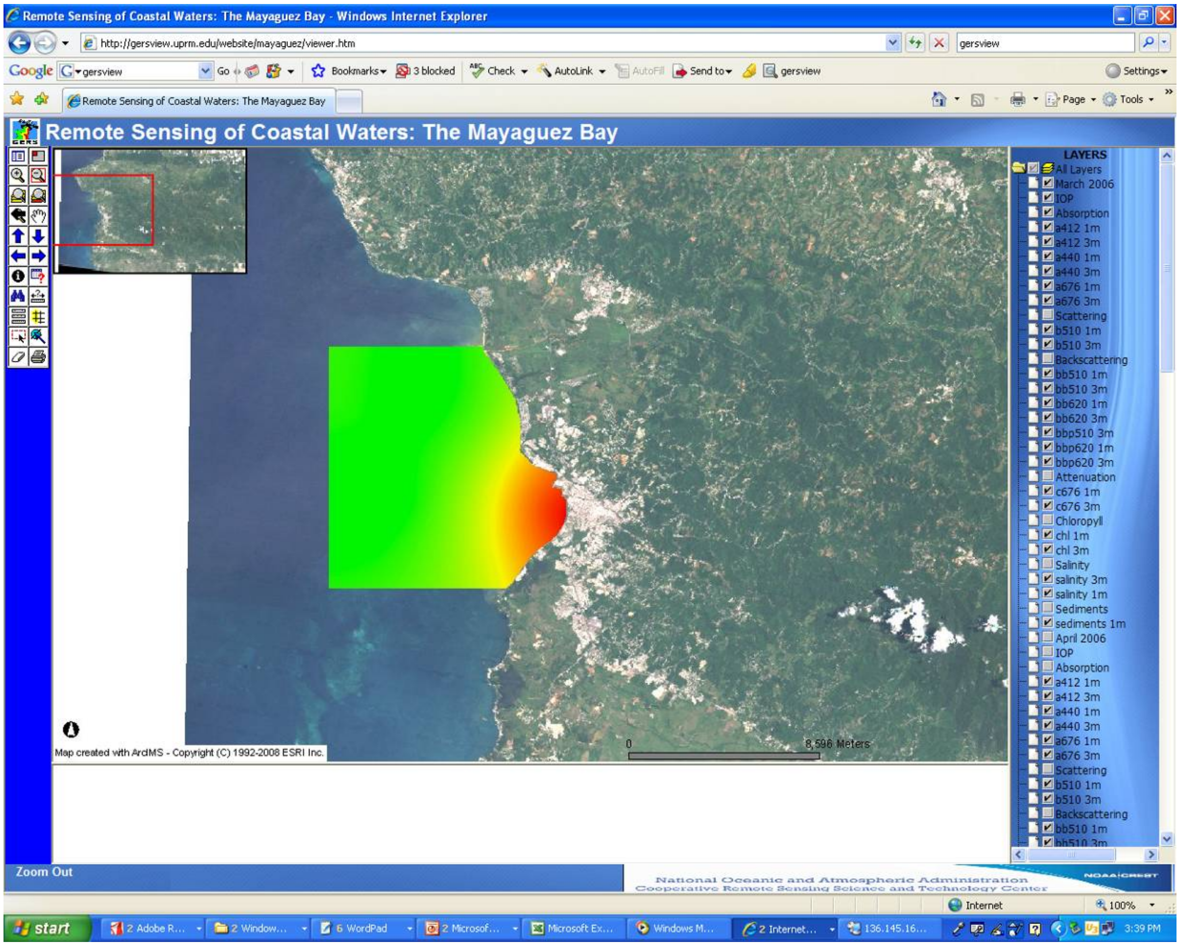


Figure 3 Screen shot of a published data set through the http://gersview.uprm.edu data portal.

COASTAL –GILBES' GROUP REPORT
(Performance period: September 1, 2008 to February 28, 2009)

RESEARCH COMPONENT

RESEARCH PROJECT SUMMARY FOR THE REPORTING PERIOD ONLY

Project	Tasks	CREST Researcher	Students involved	NOAA and Other Colloborators
Project (2) Field measurements in coastal waters for algorithm testing/development and satellite validation.	Compare to satellite water leaving products and atmosphere retrievals. Intercomparison of the below/ above water signals with aircraft and satellite data as available.	F. Gilbes	Vilmaliz Rodriguez (M.S. Student) Natlee Hernández (B.S. Student graduated in Dec 2008, now M.S. Student) Marcos Rosado (Ph.D. Student, graduated in Dec 2008)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Eric Harmsen Luis Pérez-Alegría Roy Armstrong From CSU: Carlos Ramos-Scharrón
Project (3) Improvement/ Development of algorithms for remote sensing of coastal waters.	Analysis of optical field measurement together with Chl, TSS concentrations. Evolution and tuning of algorithm for Chl retrieval in PR coastal waters. Development of GIS database for land sea interactions in Mayaguez Bay.	F. Gilbes	Vilmaliz Rodriguez (M.S. Student) Natlee Hernández (B.S. Student graduated in Dec 2008, now M.S. Student) Alexis Cruz (B.S. Student) Marcos Rosado (Ph.D. Student, graduated in Dec 2008) Ramon Lopez (Ph.D. Student, graduated in Dec 2008)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Eric Harmsen Luis Pérez-Alegría Roy Armstrong From CSU: Carlos Ramos-Scharrón

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):**

  - Dissertations:
  - ❖ Rosado-Torres, Marcos (2008) Evaluation And Development Of Bio-Optical Algorithms For Chlorophyll Retrieval In Western Puerto Rico. UPRM-Marine Sciences, 116 pages. (http://gers.uprm.edu/pdfs/thesis2_marcos.pdf)
  - ❖ López-Rosado, Ramón (2008) Photosynthetic Efficiency Of Phototrophic Plankton And Bio-Optical Variability As Influenced By Mesoscale Processes In The Eastern Caribbean Basin. UPRM-Marine Sciences, 139 pages (http://gers.uprm.edu/pdfs/thesis_ramon.pdf)

  -Journal Publications with Students:
  - ❖ Vilmaliz Rodriguez and Fernando Gilbes are finishing a paper that will be submitted soon to Remote Sensing of Environment.

  -On-line Publications:
  - ❖ Cruz-Benitez, Alexis (2008) Spectral Effect of Minerals in Sediments of Mayagüez Bay, 34 pages. http://gers.uprm.edu/pdfs/topico_alexis1.pdf
  - ❖ Hernández-Guevara, Natlee (2008) Grain Size, Composition and Spectral Response of Deposited Sediments in Mayagüez Bay, 18 pages. http://gers.uprm.edu/pdfs/topico_natlee2.pdf

  -Books:
  - ❖ Fernando Gilbes and students have continued working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM and the University of Puerto Rico Press.

- **Dollar amount of funds leveraged with CREST funds (during performance period):**

Project Title	Sponsoring Agency	PI/Co-PI/ Recipient/Group	Dollars	Start Date	End Date
Study of Benthic Habitats Using Hyperspectral Remote Sensing	NSF-CenSSIS	PI: Miguel Velez Co-PI: Fernando Gilbes among others	$50,000	March 2000	February 2010
Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands	University of Puerto Rico Sea Grant College	PI: Johannes Schelekens Co-PI: Fernando Gilbes	$30,000	June 2006	September 2009

- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Marcos Rosado, UPRM-Dep. of Marine Sciences (this student worked in a NOAA CREST related topic, but he was not directly funded by the project)
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** Nathlee Hernández, UPRM-Department of Geology (this student worked in a NOAA CREST related topic, but she was not directly funded by the project)
- **NOAA Collaborators:** A site-specific algorithm has been developed and tested to estimate Total Suspended Sediments (TSS) in Mayaguez Bay. This algorithm is being incorporated in NOAA-NESDIS system as a "testing product" of TSS for Puerto Rico in collaboration with Joaquin Trinanes, Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), and Roy Armstrong (UPRM-Department of Marine Sciences).
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Processing of field data collected in Mayaguez Bay over the past seven years was continued. A second version of a site-specific algorithm for the estimation of Total Suspended Sediments in Puerto Rica coastal waters has been developed and its implementation as "testing product of the NOAA CoastWatch program is underway.

Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. Several algorithms developed by different groups to estimate Chl-a using ocean color sensors were tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data and modeling with Hydrolight. Additional biogeo-optical data have been incorporated in GERSVIEW (the on-line GIS-database of the GERS Lab) for further analyses and comparisons with satellite data. Good progress has been obtained in all proposed tasks.

Tasks (For year III as per the Milestone Chart)

Task: Compare to satellite water leaving products and atmosphere retrievals

A large number of images were evaluated in order to select only high quality data for the application of a previously developed algorithm to estimate total suspended sediments (TSS) using MODIS band 1 data. It was found that in 2004 only 24 images were suitable for analyses; this represents approximately 6.6% of the total of images generated in one year. Presently, this algorithm is being evaluated for application to estimate TSS in all Puerto Rico coastal waters. A GIS based model is being assembled to estimate sediment load to the Mayagüez bay to compare it with same estimations derived from MODIS data. This model is based on the Revised Universal Soil Loss Equation (RUSLE), which requires to spatially defining a series of factors that promotes soil erosion. Basic information, such as LandUse, soil series and annual precipitation, was used to define these factors. The resultant values are reasonable when compare to previous studies and their spatial distribution responded to known characteristics of the area. More details of this task can be found in Vilmaliz Rodriguez report appended at the end.

Task: Intercomparison of the below/above water signals with aircraft and satellite data as available.

We validated the MODIS 1km Chlorophyll-a product for the Mayagüez Bay and analyzed the relationship of suspended sediments with this type of data. For such validation, comparisons of values directly measured in the field were compared with MODIS chlorophyll-a estimates. A correlation coefficient (R^2) of 0.0283 was obtained for Terra satellite data and 0.0265 for Aqua satellite. The R^2 between Chlorophyll-a from Aqua and Terra and the suspended sediments were 0.0267 and 0.2327, respectively. We have found that characteristics of the sediments, like composition and grain size distribution, have important implications in the optical properties of the water. The composition of the grains shows more carbonates on Añasco River and more terrigenous in Yagüez River. Along the three rivers is shown the lack of organic matter. The XRD analysis shows the presence of quartz and halite as common mineral of the study site. The reflectance curves (done with the GER-1500 spectroradiometer) demonstrate that the stations with finer grain sizes reflect more. These results will also help to understand the dynamics of suspended sediments in Mayagüez Bay and its relationship with the chlorophyll-a to provide recommendations for future application of remote sensing in this region. More details of this task can be found in Natlee Hernandez report appended at the end.

Project 3: **Improvement/Development of algorithms for remote sensing of coastal waters**

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.
- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.
- **Supervising PI or Co-Is:** Fernando Gilbes Santaella
- **Publications (during performance period):**

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  -Books:
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Project Title	Sponsoring Agency	PI/Co-PI/ Recipient/Group	Dollars	Start Date	End Date
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- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** Ramón Lopez, UPRM-Dep. of Marine Sciences
- **Students MS:** Vilmaliz Rodriguez, UPRM-Department of Geology
- **Students Undergraduate:** Alexis Cruz, UPRM-Department of Geology (this student worked in a NOAA CREST related topic, but she was not directly funded by the project)
- **NOAA Collaborators:** A site-specific algorithm has been developed and tested to estimate Total Suspended Sediments (TSS) in Mayaguez Bay. This algorithm is being incorporated in NOAA-NESDIS system as a "testing product" of TSS for Puerto Rico in collaboration with Joaquin Trinanes, Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), Luis Pérez-Alegría (UPRM-Department of Agricultural Engineering), and Roy Armstrong (UPRM-Department of Marine Sciences).
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Processing of field data collected in Mayaguez Bay over the past seven years was continued. A second version of a site-specific algorithm for the estimation of Total Suspended Sediments in Puerto Rica coastal waters has been developed and its implementation as "testing product of the NOAA CoastWatch program is underway. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer are being used to estimate these parameters and compared with MODIS data. Several algorithms developed by different groups to estimate Chl-a using

ocean color sensors were tested in Mayaguez Bay using the GER-1500 remote sensing reflectance data and modeling with Hydrolight. Additional biogeo-optical data have been incorporated in GERSVIEW (the on-line GIS-database of the GERS Lab) for further analyses and comparisons with satellite data. Good progress has been obtained in all proposed tasks.

Tasks (For year III as per the Milestone Chart)

Task: Analysis of optical field measurement together with Chl, TSS concentrations

This task is focused on the spectral response of minerals in suspended sediments of Mayaguez Bay. Rio Añasco, Yagüez and Guanajibo are the three major rivers that affect the sedimentation of Mayaguez Bay. Each river had three stations (Dentro, Boca and Playa) to obtain sediments and compare the spectral response of total suspended sediments (TSS) and without organic matter. Water samples were collected in September 21 and September 26, 2008. A laboratory procedure was developed to obtain pure minerals from the sediments and take out the organic material, which can affect the Remote Sensing Reflectance (Rrs). Rrs was obtained using the GER-1500 spectroradiometer. In general, samples with minerals only showed higher Rrs than in samples with TSS. The higher value of Rrs, in general, is related with high concentration of minerals. These results will help to develop other studies in Mayaguez Bay and will provide recommendations in remote sensing studies. More details of this task can be found in Alexis Cruz report appended at the end.

Task: Evolution and tuning of algorithm for Chl retrieval in PR coastal waters

Mayagüez Bay cruises were used with the purpose of studying phytoplankton dynamics, optically active water components and ultimately developing bio-optical algorithms for the estimation of chlorophyll a (Chl a). Fourth derivative spectroscopic analyses were applied to phytoplankton absorption spectra in order to determine phytoplankton pigments that could be identified as chemotaxonomic markers and to quantify Chl a. Good correlation was found between in situ Chl a concentration and the fourth derivative peaks associated to photosynthetic pigments. Surface Rrs spectra were modeled with Hydrolight using a four component case 2 model with in situ data for input. It was determined that for the range of Chl a values normally observed in Mayaguez Bay (0.1 to 1 μg l-1), mineral values over 5 mg l-1 were sufficient to mask the Chl a signal. These results were used to tentatively set a TSS threshold of 5 mg l-1 over which Chl a concentrations cannot be derived from the Rrs spectra. Three empirical algorithms were developed for Mayagüez Bay. The quasi-analytical algorithm (QAA) from Lee et al. (2002) was also evaluated with Mayagüez Bay data. More details of this task can be found in Marcos Rosado Dissertation at http://gers.uprm.edu/pdfs/thesis2_marcos.pdf

Task: Development of GIS database for land sea interactions in Mayaguez Bay

Quality control of all data collected in Mayaguez Bay was continued during the reported period. In addition, new analyses of the collected radiometric data were started. This data set was not included during the first round of processing because the nature of processing and quality control is more complicated and requires particular attention. Transfer of knowledge between Ramon Lopez (Ph.D. student graduated in Dec 08) and Natlee Hernandez (new M.S. student) started in order to continue the implementation and further development of GERSVIEW. More details of this task can be found in Ramón Lopez report appended at the end.

Future Tasks (From the Milestones)

Efforts for developing site-specific algorithms for suspended sediments will continue. Other optical data are being organized and they are getting ready for the GIS databases. Very soon they will be exported to ArcIMS and be published in the web. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay. Natlee Hernandez (new M.S. student), will continue working with this important aspect of the project. A publication by Vilmaliz Rodriguez will be submitted to the Remote Sensing of Environment journal very soon. She is also working in another paper related with the second chapter of her thesis. The PI and other students will continue working with the chapters of the Mayaguez Bay book.

Using GIS and Remote Sensing techniques to estimate suspended sediment load in a Tropical Open Bay

Vilmaliz Rodríguez and Fernando Gilbes
Department of Geology, University of Puerto Rico in Mayagüez

Abstract

A large number of images were evaluated in order to select only high quality data for the application of a previously developed algorithm to estimate total suspended sediments (TSS) using MODIS band 1 data. It was found that in 2004 only 24 images were suitable for analyses; this represents approximately 6.6% of the total of images generated in one year. Presently, this algorithm is being evaluated for application to estimate TSS in all Puerto Rico coastal waters. A GIS based model is being assembled to estimate sediment load to the Mayagüez bay to compare it with same estimations derived from MODIS data. This model is based on the Revised Universal Soil Loss Equation (RUSLE), which requires to spatially define a series of factors that promotes soil erosion. Basic information, such as LandUse, soil series and annual precipitation, was used to define these factors. The resultant values are reasonable when compare to previous studies and their spatial distribution responded to known characteristics of the area.

Introduction

This project has focused on the development of site specific algorithms to estimate TSS by deriving empirical relationships between total suspended sediments TSS, optical backscattering (b_b), *in situ* remote sensing reflectance (R_{rs}) and MODIS data. Currently this component of the study is in the validation stage and being evaluated to generate operational products. One of the expected applications of these algorithms is not limited to generate products of TSS but also use this information to estimate absolute values of TSS in kg/m^3. This will provide very useful information that can be related to landward processes such as flux of sediments. In order to better understand these relations, GIS techniques will be incorporated in the analysis for estimations of suspended sediment load.

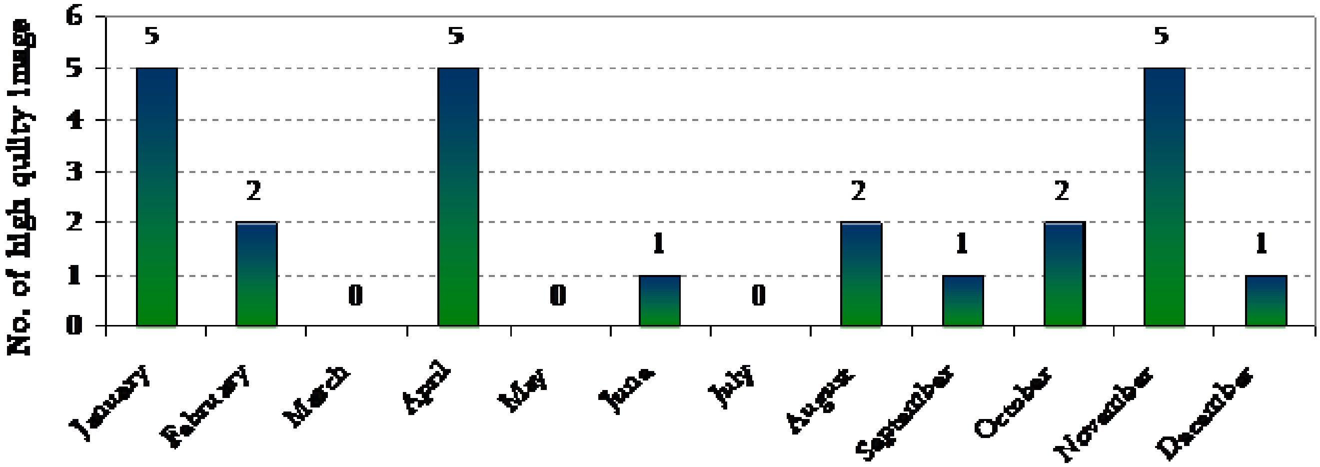
Coastal environment dynamics are highly influenced by landward fluvial processes, such as soil erosion and sediment deposition and transport. Different types of sources contributing to the sediment budget of a watershed includes: landslides, debrisflows, gullies, treethrow and animal burrows. However, it is difficult to account for all these considerations by identifying and classifying all of them in a single model, especially if the study area has a large extension. This is the case of Mayagüez Bay watershed which has an area of 915 km^2 which include Añasco, Guanajibo and Yagüez rivers watersheds (Fig. 1). The Revised Soil Loss Equation (RUSLE) provides a simple method to estimate the amount of soil loss, caused by sheet and rill erosion, occurring in a determined area for one year (Wischmeier, 1976). Products of this equation are normally used to identify areas with higher potentiality of soil erosion and determine the effect of land use changes in sediment production in small watersheds (Onyando et al., 2005; López et al, 1998; Cartwright, 2002). In this study the equation product is combined with sediment delivery ratios information to generate an estimation of total suspended load to the bay for a specific year. The product of this equation will be combined with estimations of SS by MODIS data to raise a study that helps to better understand land-sea interaction processes. This report includes the preliminary results obtained in this component of the study in this stage.

Estimating TSS using MODIS data

A previously developed algorithm to estimate TSS using MODIS band 1 data was submitted to Joaquín Trinanes, a person in charge of the management of coast-watch image processing and product generation. The expectation is to generate TSS operational products for Puerto Rico Coastal Waters. Various recommendations are being evaluated such as perform of additional preprocessing routines using SeaDAS (MSL12) and use exponential instead of linear equation, in order to improve the algorithm application.

Summary of 2004 images downloaded

All MODIS-Terra 2004 images that included the Mayagüez Bay Area were evaluated. After evaluation in an image processing software (ENVI 3.X), only 24 images were selected for further analyses. The TSS algorithm will be applied to these images when the recommendations offered (by Joaquín Trinanes) are incorporated in the analysis. Generated products will be compared with discharge data of the rivers flowing into the bay (Añasco, Guanajibo and Yaguez Rivers).



Graph 1

Defining RUSLE factors

A model is being developed to estimate soil erosion in the Mayagüez Bay watershed (Fig. 1). The Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997) measures total soil loss, in units of tons/acre/year, by multiplying different factors associated with erosion by water. Basic information was required to spatially define the factors of this equation.

$$A = R * K * L * S * C * P$$

Where,

A= Soil erosion (Tons/acre/year); **R**= Rainfall factor; **K**= soil erodability factor; **L**= Slope length factor; **S**= Slope steepness factor; **C**= Cover and management factor; **P**= erosion control practice factor. The P factor was not included due to the lack of data.

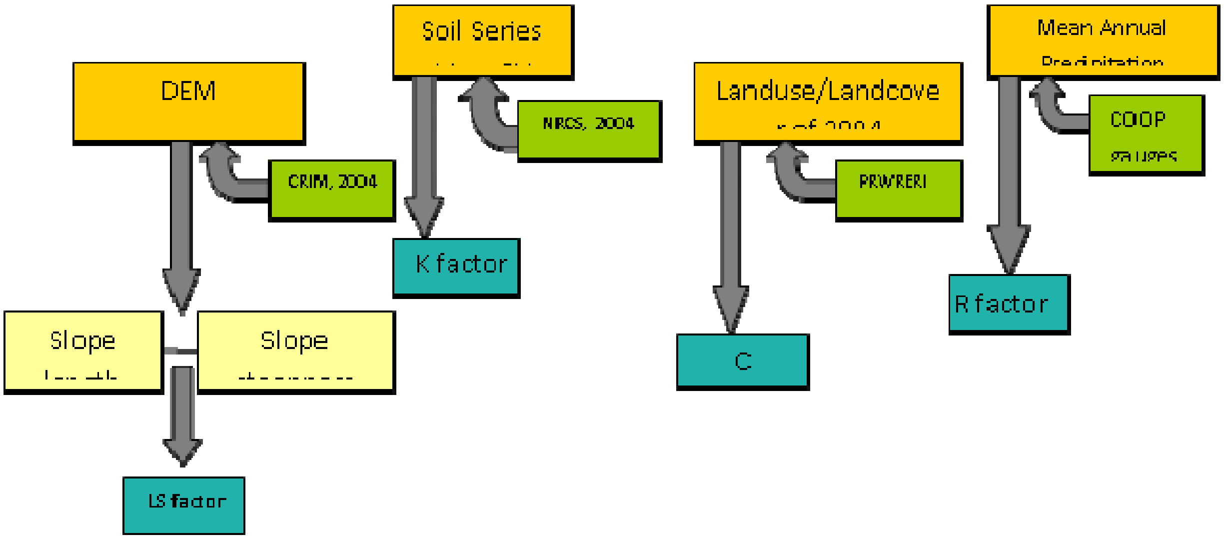


Figure 2 illustrates information related to the origin of the data used to define all the factors:

Rainfall factor

The input information used to define the Rainfall factor was total annual precipitation measured in 15 gauges stations in 2004 (Fig. 3). The following linear equation was defined by López et al. 1998 and it was used to calculate the R factor.

$$y = 0.2629x - 11.06$$

Figure 3

The Spatial Analyst extension of ArcGIS 9.2 (ESRI, 2002) was used to produce a R factor raster grid (Cell size= 10 m) for all the study. This extension has four interpolation methods: Inverse Distance Weighted, Spline, Kriging and Natural Neighbors. Interpolation tests were made using all the methods and the results that better responded to the properties of this parameter were the generated using the Spline method. The Spline method is a general-purpose interpolation that fits a minimum-curvature surface trough the input points (ESRI, 2002). The following figure illustrates some of the results obtained with the different interpolation methods.

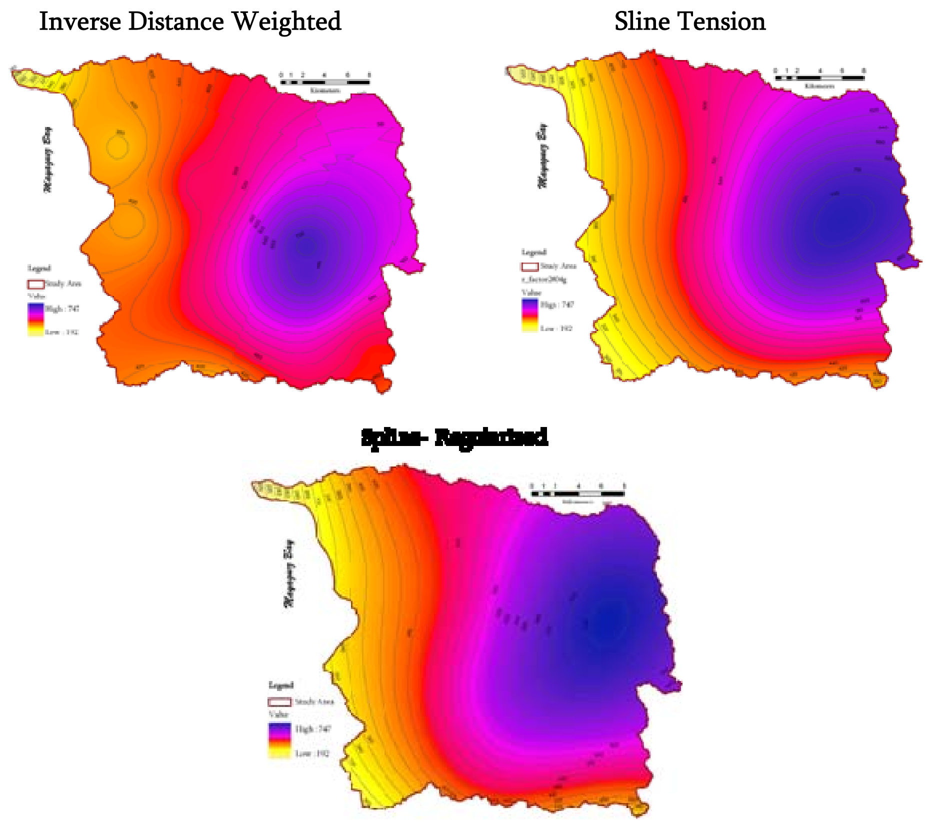


Figure 4

K factor

Based on digital soil survey data (USDA-NRCS) and a RUSLE attribute table downloaded from the website of this agency, the K factor was defined for all the study area (Fig. 5).

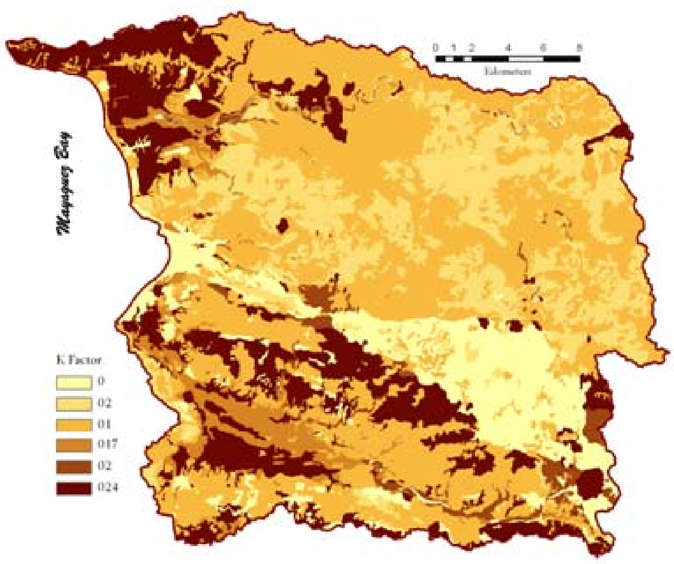


Figure 5

C Factor

The C factor was defined based on a LandUse classification developed by the Puerto Rico Water Resources and Environmental Research Institute (PRWRERI) in 2004. Although this is a very detailed classification, for the purposes of this study it was not necessary all he information provided therefore it was reclassify to this general classes:

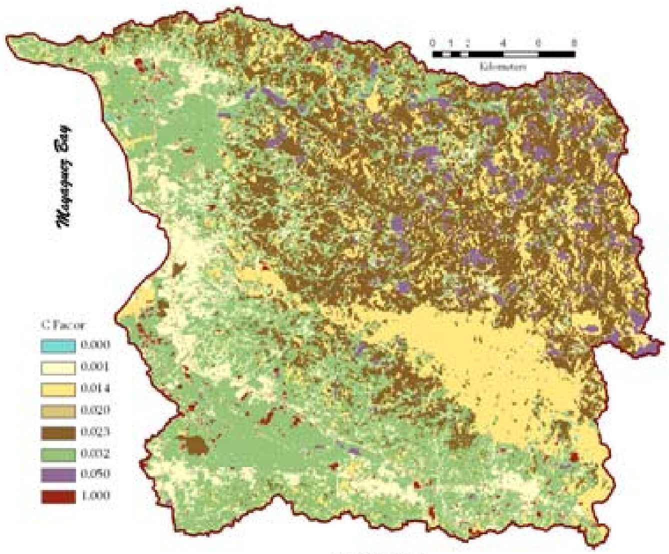


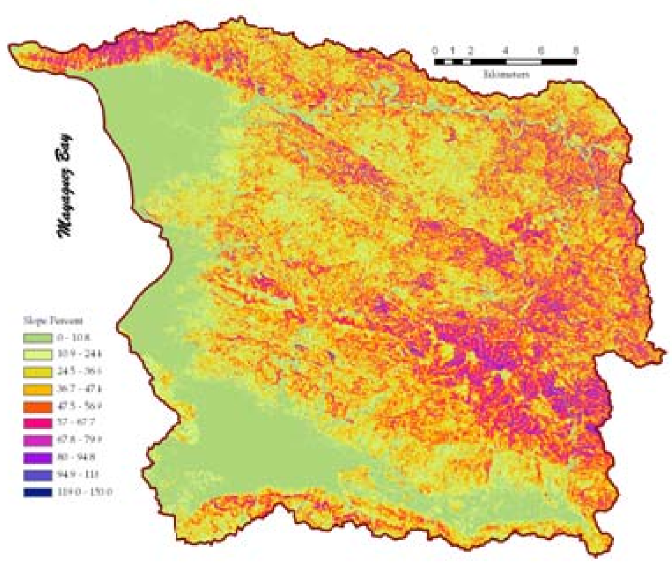
Figure 6

Class	C Factor
Water	0.000
Dense Urban	0.001
Closed Canopy	0.014
Less Dense Urban	0.020
Open Canopy Forest	0.023
Pasture	0.032
Agriculture	0.050
Barren Land	1.000

López et al., 1998

Slope and Length Factor

A set of high resolution (10 m) DEMs were processed to produce a single elevation grid for all the area, which is the basic input information to define the slope and length factor. The slope (percent) was calculated using this grid as an input in a routine available in the Spatial Analyst extension (ArcGIS 9.2, ESRI). The only factor that still needs to be defined is the length factor to estimate soil erosion (*A*).



Conclusion

An effort that is aiming to produce TSS operational products for Puerto Rico coastal waters is in progress. However, the availability of good quality images remains significant limiting factor for the development and application of algorithms in this area. GIS techniques will be used to estimate suspended sediment load to Mayagüez Bay. Most of the factors included in the model were defined based on the Revised Universal Soil Loss equation and the resultant values and spatial distribution corresponded to known properties of the area.

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ESRI, 2000-2002. Using ArcGIS 3D Analyst (ArcGIS 8.3 user manual), p.72-75

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Wischmeier, W.H. 1976. Use and misuse of the universal soil loss equation. Journal of Soil and Water Conservation, 31: 5-h9.

Understanding the spectral response of suspended sediments on Mayagüez Bay

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I. Abstract

The Mayagüez Bay is a difficult study area because has the influence of three rivers, have shallow and deep waters and reefs in a very small area. The application of remote sensing to this area isn't straight forward like in other coastal environment. In this study we validate the MODIS 1km of chlorophyll-a product for the Mayagüez Bay and analyze the relationship of suspended sediments with this type of data. Also, because the validation was rejected, suspended sediments are affecting the signal received by remote sensors; it is necessary to better understand their characteristics. For the validations of the chlorophyll-a, comparisons of its values directly measured in the field, with MODIS chlorophyll-a and suspended sediments are presented. A correlation coefficient (R^2) of 0.0283 was obtained between MODIS chlorophyll-a from the Terra satellite and the field chlorophyll-a. In the case of Aqua satellite the R^2 was 0.0265. The correlation of the suspended sediments and the Chlorophyll-a, both from the field was 0.0903. The R^2 relations between Chlorophyll-a from Aqua and Terra and the suspended sediments were 0.0267 and 0.2327 respectively. By the other side, the characteristics of the sediments, the grain size distribution demonstrates that the offshore stations have grains with lower diameter than the onshore samples. The composition of the grains shows more carbonates on Añasco River and more terrigenous in Yagüez River. Along the three rivers is show the lack of organic matter. The XRD analysis shows the presence of quartz and halite as common mineral in the samples. The reflectance curves (done with the GER-1500) demonstrate that the stations with finer grain sizes are A2, Y2 and G2, reflects more than the others in the dry measures. These results will also help to understand the dynamics of suspended sediments in Mayagüez Bay and its relationship with the chlorophyll-a to provide recommendations for future application of remote sensing in this region.

Key words: Chlorophyll-a, MODIS, sediments, reflectance, physical characteristics.

II. Introduction

The oceans represent around 71% of the Earth, which means that they have a great influence in our lives, including the food. The food chain in the ocean begins with the phytoplankton. These important microscopic plants take up essential nutrients to produce carbohydrates (Stout, 2007), which are also vitals for other marine organisms. To understand more the phytoplankton behavior on the Bay there were analyze MODIS imagery along five years (2001-2006). MODIS is onboard Aqua and Terra satellites were used. This satellite has 36 bands, but currently from 8 to 36 (with a spatial resolution of 1Km) is used for the estimation of Chlorophyll-a (Cardwell, 1999). Terra satellites have its orbit around the Earth from north to south across the equator in the morning and Aqua passes south to north over the equator in the afternoon (Cardwell, 1999).

By the other way also exist the geological factor in this environment because we have the river discharges along the Bay. Is very important to describe the two seasons (rainy and dry) of the year that affect more this rivers discharges. Each season has a large influence in the dynamics and amount of sediments in the Bay. During the rainy season, river discharge controls the concentrations of suspended sediments. During the dry season a large amount of sediments are re-suspended due to strong waves (Fernando Gilbes, personal communication). Recurrent cold fronts that travel across the Caribbean region during winter produce such wave action. Since this research project will take place during this winter-spring semester, it will focus on the dynamics of re-suspended sediments from the bottom. In this study case, sediments are re-suspended by the effect of the cold fronts. A front is the transition zone between two air masses of different temperatures and a cold front occurs when cold dry stable polar air is replacing warm and moist air (Donald, 2007). The repeated cycling of cold-front passages leads to positive feedback with transport onshore during both pre- and post-front conditions, and effective attenuation of wave energy over the muddy inner shelf inhibits erosion at the coast (Kineke et al., 2006).

Mayagüez Bay is located at 18° 10' N and 18° 16' N of latitude and 67° 10' W and 67° 14' W of longitude. This Bay is affected by the discharge of the Güanajibo, Yagüez and Añasco rivers (Figure 1). However, for this study its bathymetry (depth conditions) is also very important. The southern region of the bay is shallower than the northern region, which produces more re-suspension there due to wave action (Fernando Gilbes, personal communication). The sediments and nutrients from these rivers also affect the phytoplankton dynamics of the Mayagüez Bay.

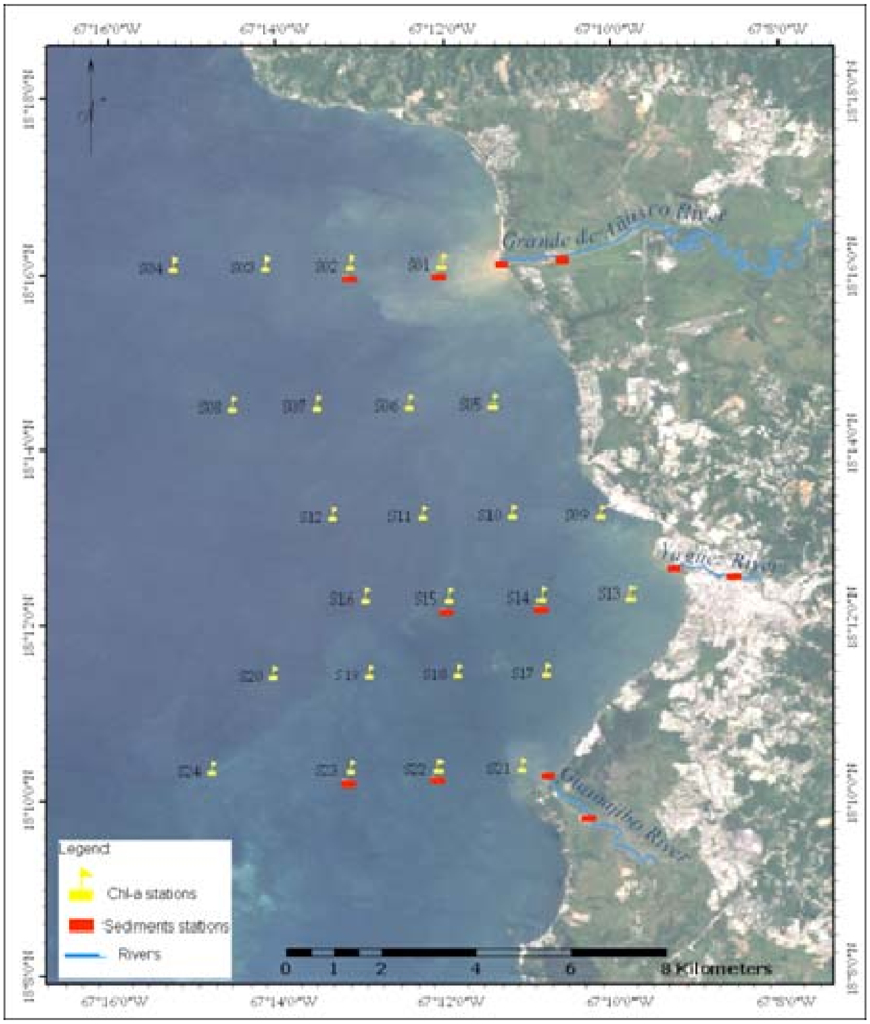


Figure 1: Study area and proposed sampling stations (adapted from Hernández, 2008)

The geology of the Mayagüez Bay is composed by Alluvium of the Quaternary. But it is not the only formation that is important in this area. The geology of the river's basin that discharge into this Bay is also important. One of them is the Güanajibo River located at the south of the Bay. The formations that compose this river basin are from CaboRojo, whose most abundant rock is the serpentinite. North to it, we found the Yagüez River, which is composed by the Yauco Formation. The Yauco Formation is composed of volcanic sandstone, siltstones, mudstones, claystone and limestone and the most abundant minerals are calcite, chlorite, epidote and quartz. Another formation that has effects in the clasts and sediments that arrive in the Mayagüez Bay is the Maricao Formation. It is composed by volcanic breccia with large phenocrysts, conglomerates, volcanic sandstone and limestones. The most common minerals are augite, plagioclase, hornblende and magnetite. The last unit through which the Yagüez River cuts is one composed by porphiriticaugite basalts. It also has minerals scaprolite, plagioclase, magnetite and olivine (Curet, 1986). Those are the compositions of the sediments that are discharged into the Mayagüez Bay (Figure 2). The concentration of sediments derived from bottom sediment re-suspension or discharge of sediment-laden rivers is highly variable over a wide range of time and space scales (Miller and McKee, 2004). Therefore their changes affect the measured Chlorophyll in these coastal areas.

Figure 2: Geologic map of the Mayagüez area

III. Methodology

PhytoplanktonDynamics

The first step in this research was download the images from the NASA Ocean Color website. The webpage has the capacity to let the users choose the sensor and the satellite, the specific date and the region of interest, in this case, the Caribbean. After all the images from the sampling dates (Appendix 1) were downloaded for the Aqua and Terra satellites, the next step was to process the images.

The used NASA webpage shows the swats files from the specifications provided. Also we have the opportunity to choose the level of the image. They are from level 0 (completely raw), level 1A, level 1B (both partially processed) and level 2 (processed products). I choosed the images at level 1A, which were processed on the NASA-developed SeaDAS software. Here the level 1A images were geo-processed and change to level 1B and finally level 2 (Figure 4).

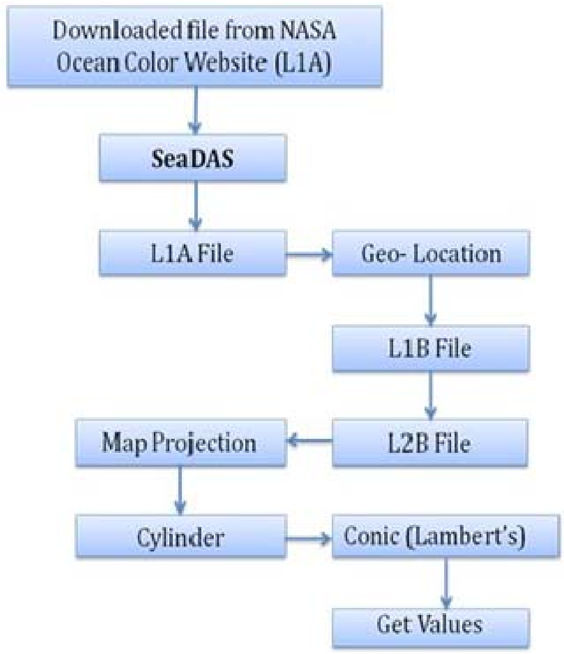
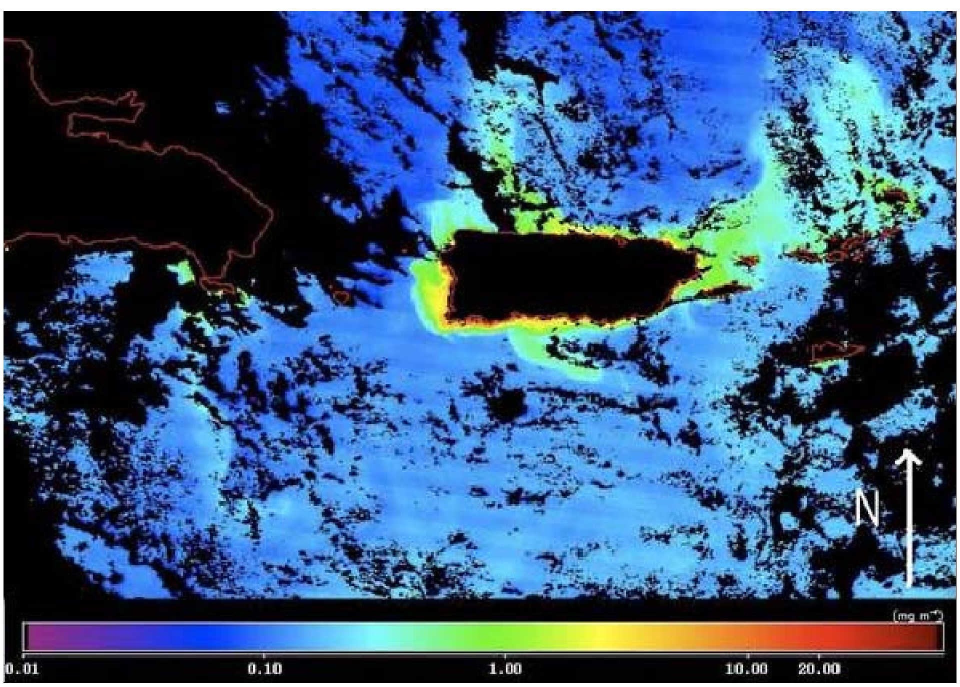


Figure 3: Flow Chart of the process to acquire the chlorophyll-a.

The next step was to correlate MODIS and field data. Finally, the accuracy of the MODIS images with 1Km of spatial resolution for the Mayagüez Bay was established.



Example of a MODIS image for the Terra Satellite processed in SeaDAS

Sediment Characteristics

The first step of this project is the collection of 11 samples and their laboratory analyses. These samples will be collected from the bottom along the Mayagüez Bay, in the west coast of Puerto Rico (Figure 1). The sampling stations will be located considering the mouth of the three main rivers: Añasco, Yagüez and Guanajibo. Five additional samples will be taken offshore for comparison (Figures 4a and 4b). The grain size and composition of the sediments collected from the bottom will be analyzed in the laboratory using standard techniques.

Figure 4a: Vessel Pez/Mar used for offshore sampling.

Figure 4b: Sampling with the sediment grab.

Granulation was use for the grain size using a sieve shaker (Figure 5). The sieves sizes utilized were 0.25Φ, 1 Φ, 2.75Φ, 3.50Φ, 3.75Φ and 4Φ (Table 1). To calculate the diameter of the grains in mm, the following formula was used:

$$D = D_0 \, x \, 2^{-\Phi};$$

Where D= diameter, D_0 =reference diameter (equal to 1 mm) and Φ is the sieve size (Krumbein, W. C. andSloss, L. L.,1963)

Table 1: Sieves sizes in Φ and mm

	1.
5	4
	0
5	5
0	9
5	7
	25

Figure 5: Sieve Shaker

The mineral compositions will be measured using the XRD machine. For this test is not necessary to pulverize the sample, only to dry them in an oven. The grain size used for this test is 4Φ and PAN.

Another test will be the percentage of carbonates or the terrigenous material. First the sample will be dried in an oven on a previously weighed glass slide 10% HCl is then added to the dry sediments to dissolve the carbonate present. They are weighted again and on the basis of the difference in weights, the percent of carbonates is determined. The remaining portion is the terrigenous material. The organic component is determined by adding

NaClO at 10% instead HCl. Also for this test a grain size of 4Φ and PAN were used.

Reflectance spectra in the visible and infrared regions also were measured in the laboratory. The GER-1500 spectroradiometer with a spectral range from 400 to 1050 nanometers will be used to determine the reflectance in the visible and near infrared regions (Chiques, 2005). The HR-1024 spectroradiometer were used to make the reflectance measurements in the mid and far infrared regions.

IV: Results

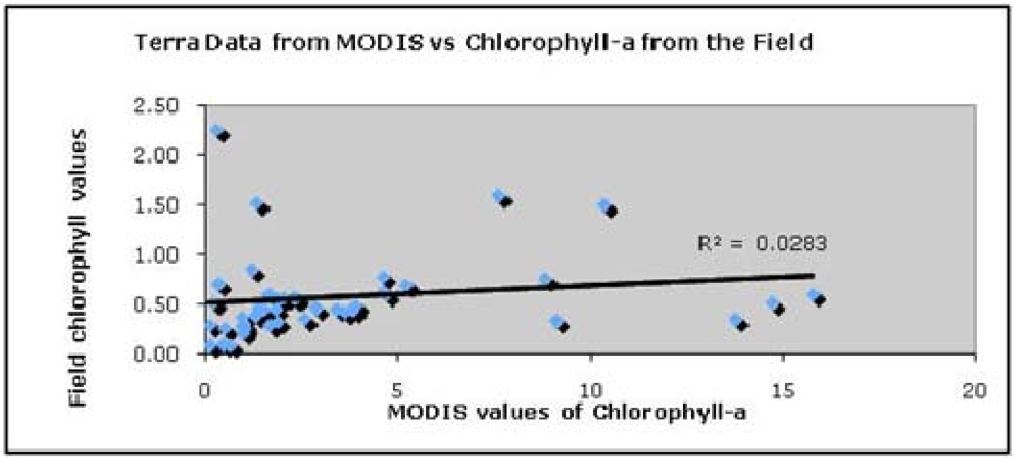
Phytoplankton Dynamics

The results of this project demonstrate that the spatial resolution of the MODIS images is too large to for Mayagüez Bay. The correlation values were very low due to several reasons. Among the most important are the atmospheric conditions and the fact that we are working in coastal waters, were the optical signal is very complicated. The average percent of good values for the Aqua satellite was 9% and for the Terra satellite was 39.6% (Table 2).

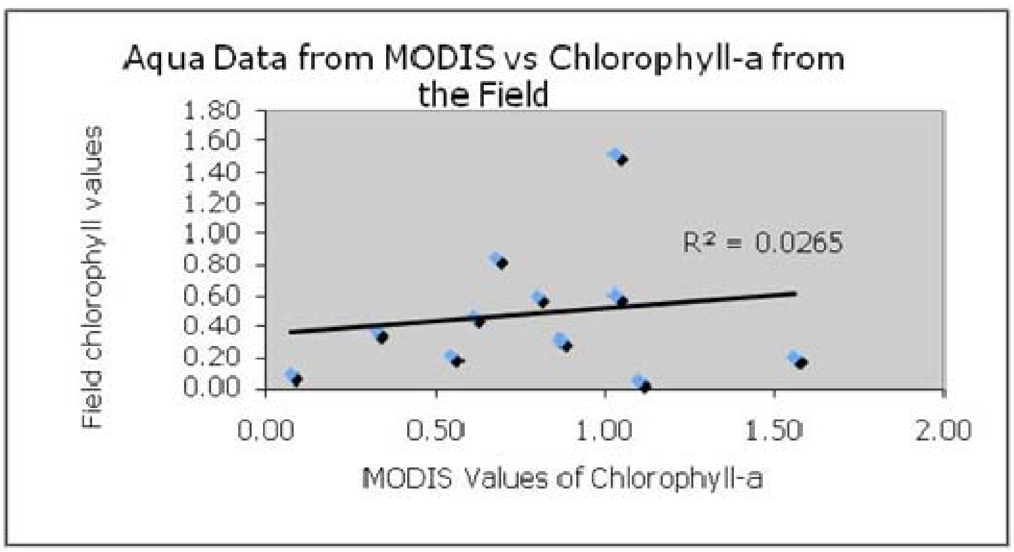
Date	Satellite	Used Data	Comments
April 24-26, 2001	Aqua & Terra	0%	Satellite not available
October 2-4, 2001	Aqua & Terra	0%	Satellite not available
February 26-28, 2002	Aqua & Terra	0%	Satellite not available
August 20, 21, 22, 2002	Aqua & Terra	0%	Clouds
February 25, 26, 27, 2003	Aqua	8.3%	Clouds
February 25, 26, 27, 2003	Terra	66.7%	Clouds
October 7, 8, 9, 2003	Aqua	0%	Not image available for Puerto Rico
October 7, 8, 9, 2003	Terra	33.3%	Clouds
January 12, 13, 14, 2004	Aqua	44.4%	Clouds
January 12, 13, 14, 2004	Terra	66.7%	Clouds
12-Feb-04	Aqua	0%	Clouds
12-Feb-04	Terra	60%	Clouds
19-Aug-04	Aqua & Terra	0%	Clouds
10-Mar-05	Aqua	100 %	-
10-Mar-05	Terra	33.3%	Clouds
19-Jul-05	Aqua & Terra	0%	Clouds
17-Aug-05	Aqua	0%	Clouds
17-Aug-05	Terra	16.7%	Clouds
20-Sep-05	Aqua & Terra	0%	Clouds
19-Oct-05	Aqua	0%	Clouds
19-Oct-05	Terra	83.3%	Clouds
6-Dec-05	Aqua	0%	Clouds
6-Dec-05	Terra	66.7%	Clouds
8-Mar-06	Aqua	0%	Clouds
8-Mar-06	Terra	66.7%	Clouds
21-Apr-06	Aqua & Terra	0%	Not image available for Puerto Rico
26-Sep-06	Aqua & Terra	0%	Clouds
26-Oct-06	Aqua	100%	Clouds
26-Oct-06	Terra	50%	Clouds

Table 2: Percentages of imagery used to determine chlorophyll-a

The correlation coefficient (R^2) between the field chlorophyll-a and the MODIS chlorophyll-a was 0.028 for Terra and 0.026 for Aqua (Graph 1 & 2). Factors that affect this correlation are the lack of values and the big spatial resolution.

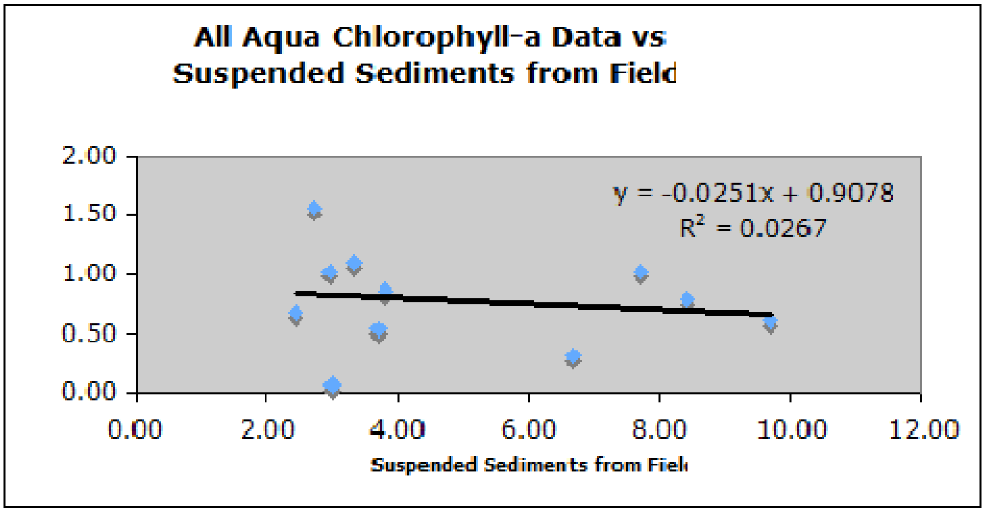


Graph 1:Correlation of the Chlorophyll-a between field and MODIS Terra data.

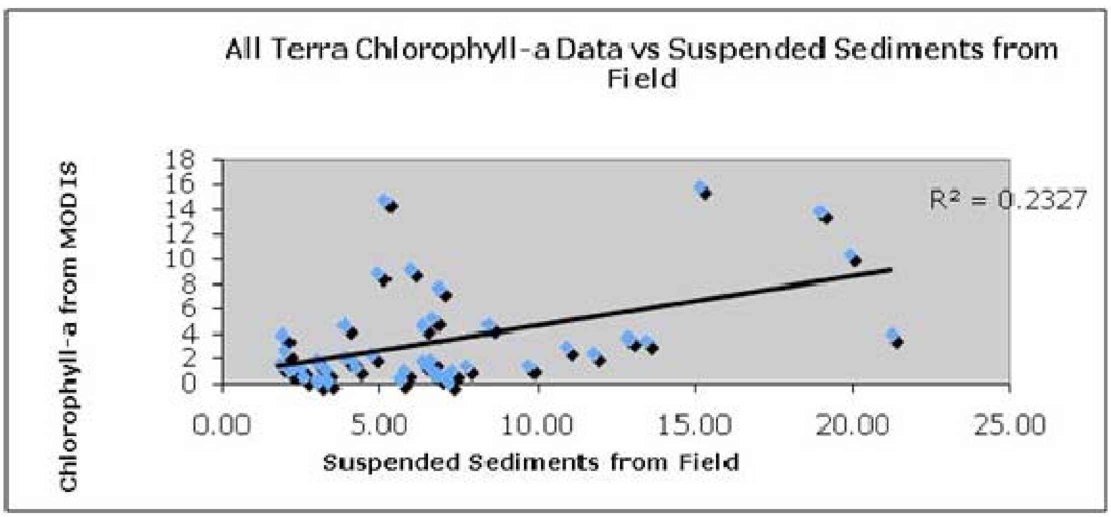


Graph 2: Correlation of the Chlorophyll-a between field and MODIS Aqua data

Correlations for the MODIS Chlorophyll-a and the suspended sediments concentration from the field were also low for the Aqua satellite but they were higher for Terra.



Graph 3: Correlation of the Chlorophyll-a as measured with MODIS at Aqua and the field suspended sediments

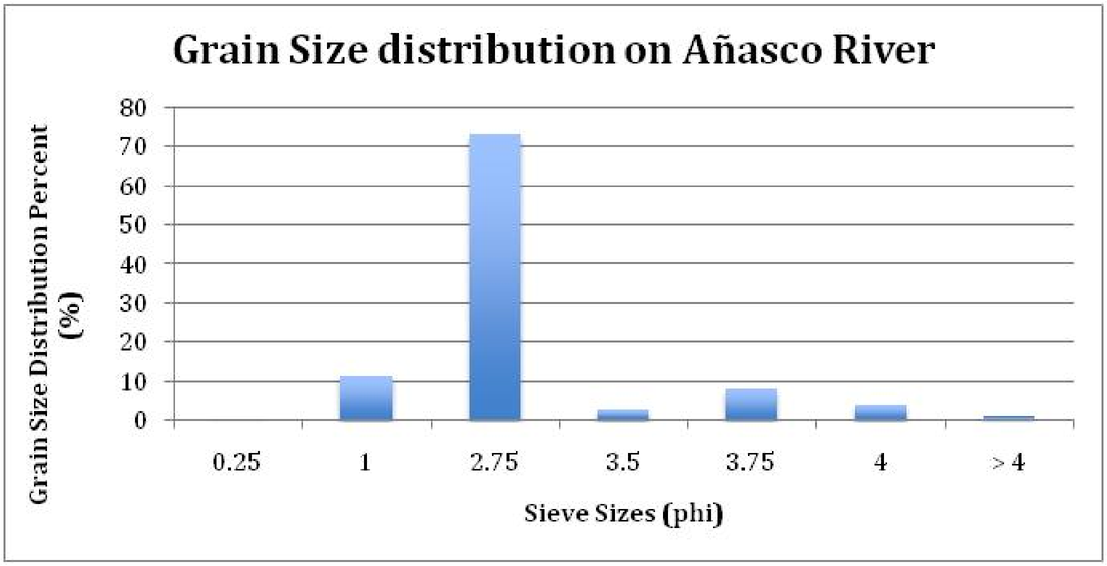


Graph 4: Correlation of the Chlorophyll-a as measured with MODIS at Terra and the field suspended sediments

Sediment Composition

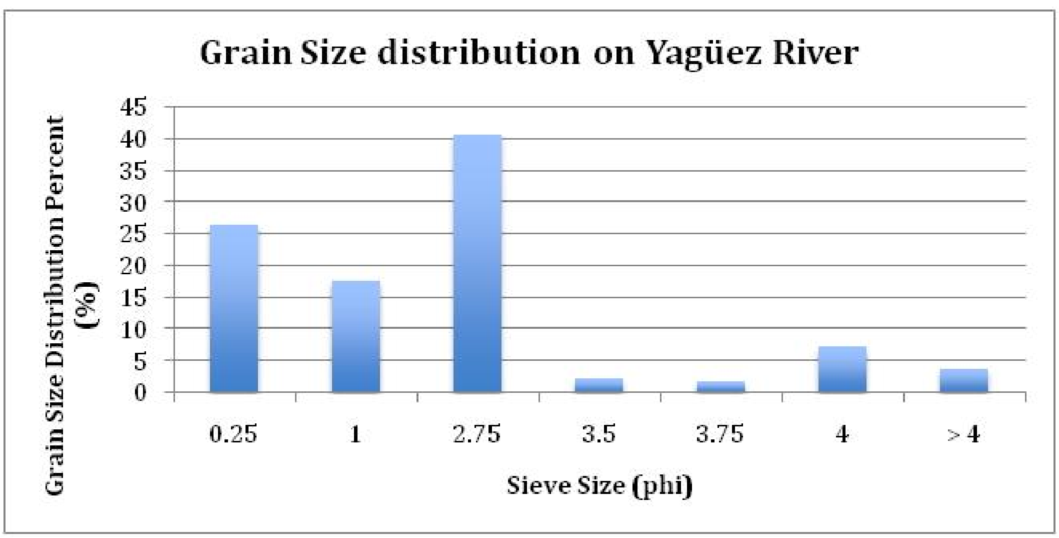
Grain size Distribution

The grain size distribution along the three rivers was determined by different grain sizes. For Grande de Añasco River the dominant grain size is for 2.75Φ of diameter, showing a fine sand size.



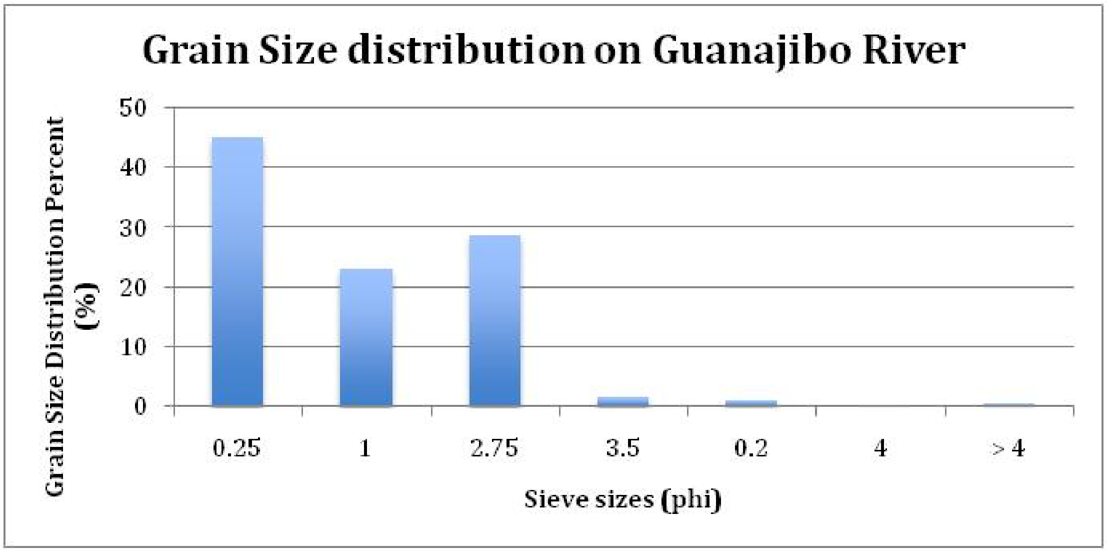
Graph 5: Grain size distribution for the Añasco River.

The grain size distribution for the Yagüez River is very influenciated by very coarse sand to fine sand. The dominant grain size in this river is from 0.25 Φ to 2.75 Φ on the Y1, Y3 and Y4 stations but in the Y2 we have a large percent on more fine grains.



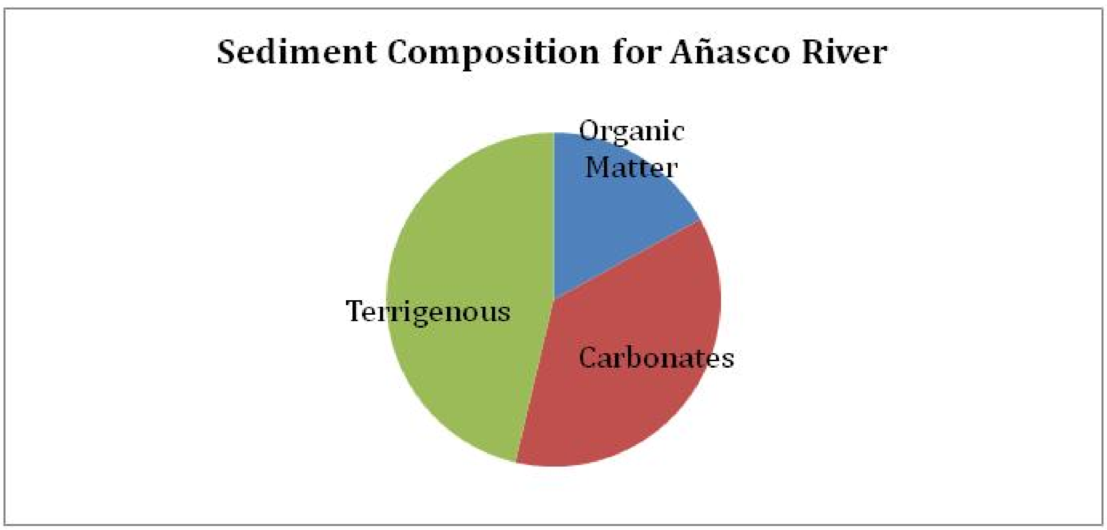
Graph 6: Grain Size Distribution for the Yagüez River.

For the Guanajibo River, we have a that the dominat grain size is of 0.25Φ to 2.75Φ of diameter. Which implies a very coarse to fine sand sizes. For the G2 station the fine grains amount increases.



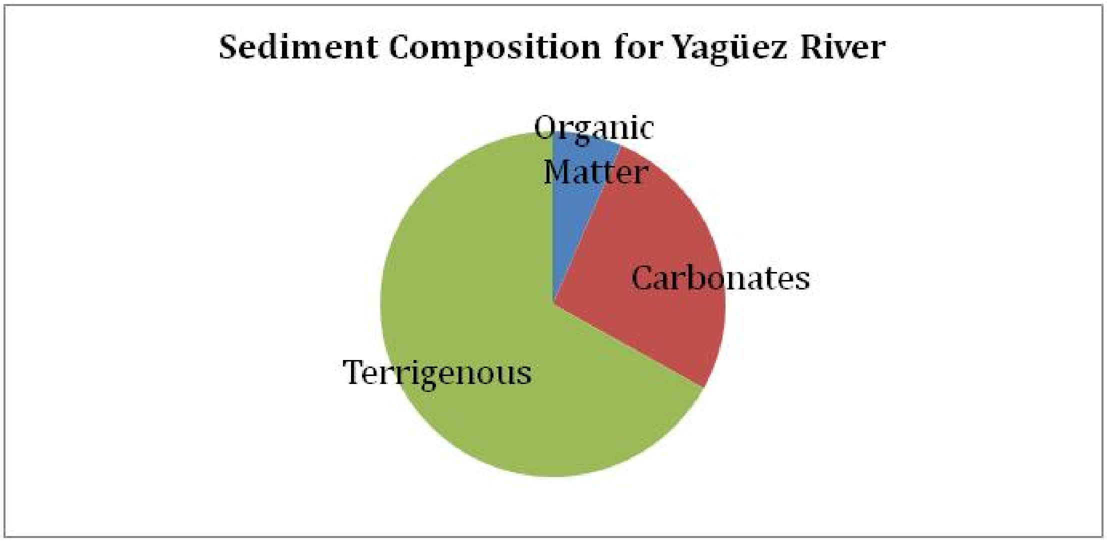
Graph 7: Grain size distribution for the Guanajibo River

The grain composition for the Añasco River is by carbonates; also have a similar amount of terrigenous and a less amount of organic matter.



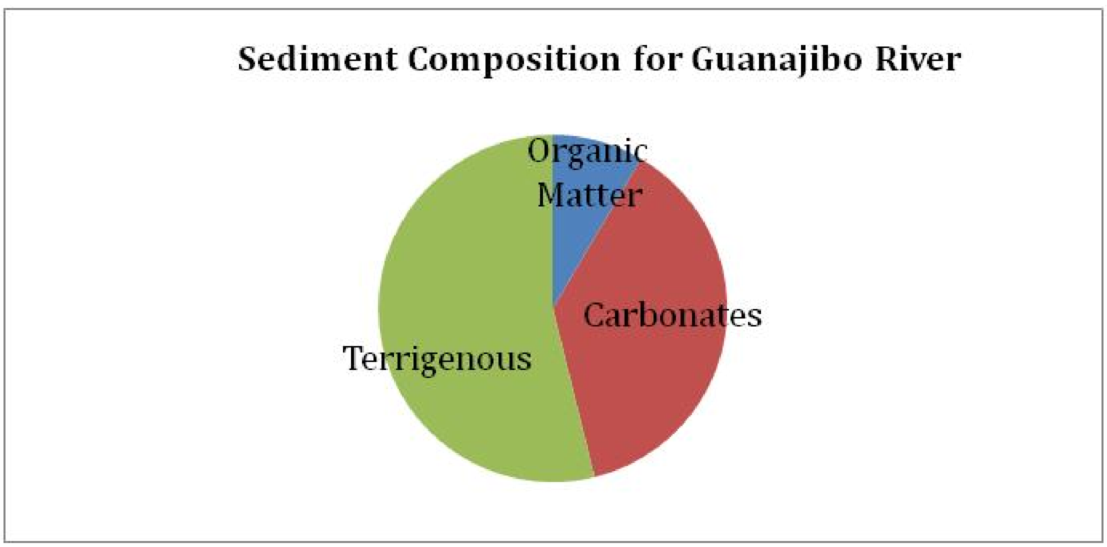
Graph 8: Composition of the sediments for the Añasco River

The grain composition of the Yagüez River is terrigenous material, followed by the carbonates and a little amount of organic matter.



Graph 9: Composition of the sediments for the Yagüez River

For the Guanajibo River we have a dominant composition of terrigenous grains, followed by the carbonates and a lower amount of organic matter.



Graph 10: Composition of the sediments for the Guanajibo River

-

Mineral Composition

The XRD shows that the quartz and the halite are the most common minerals on the samples. Quartz is present in the following samples: A2, A3, Y2, Y3, Y4, G3 and G4. By the other way, halite is present in A1, G1, G2, G4, Y1 and Y2.

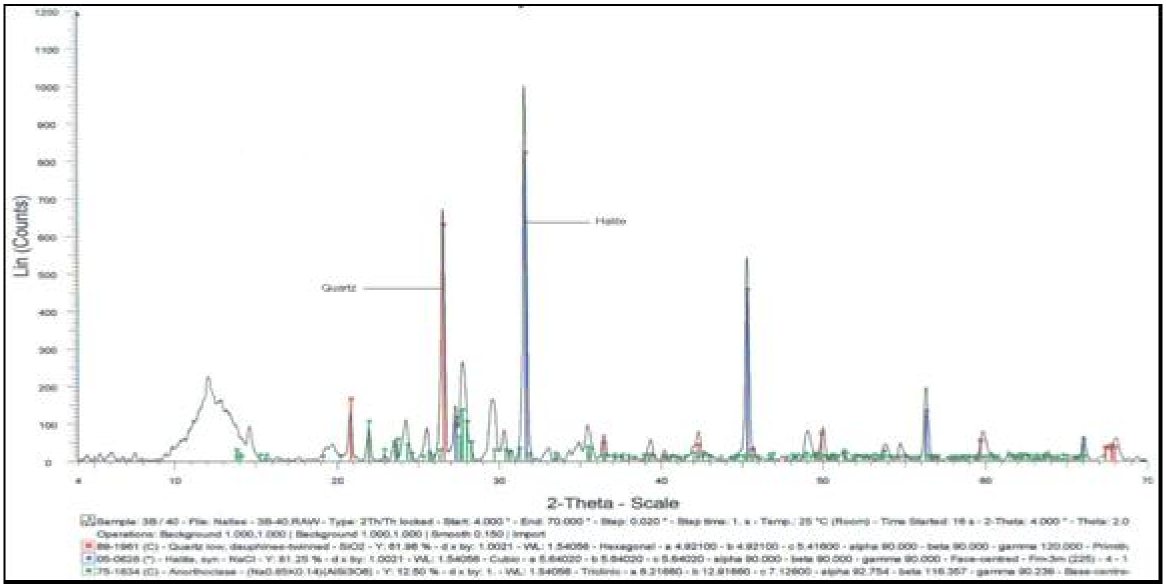
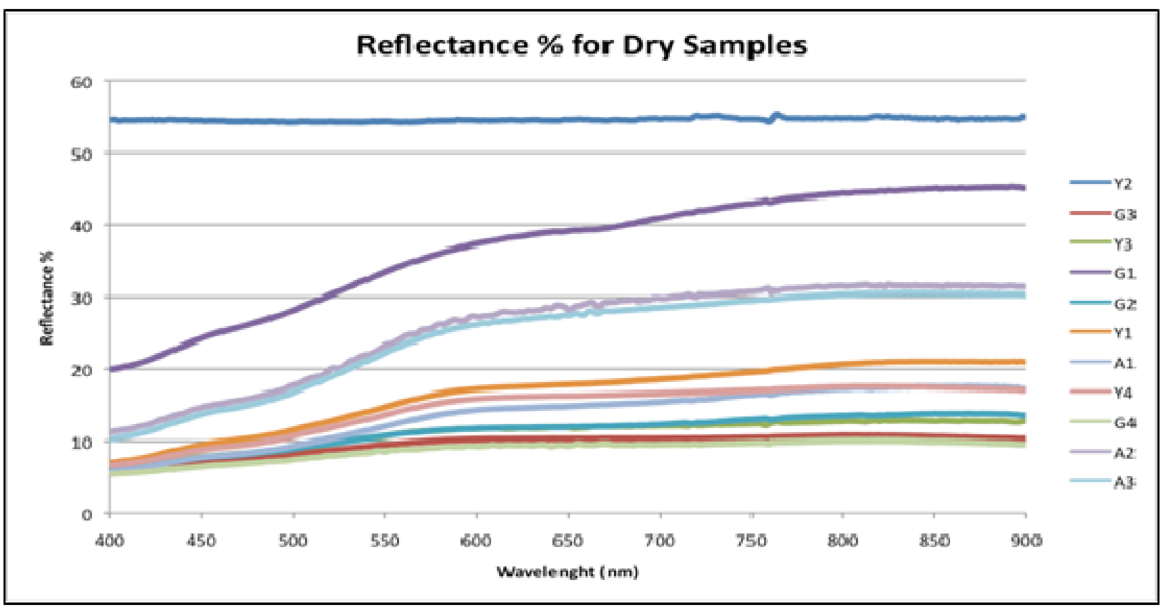
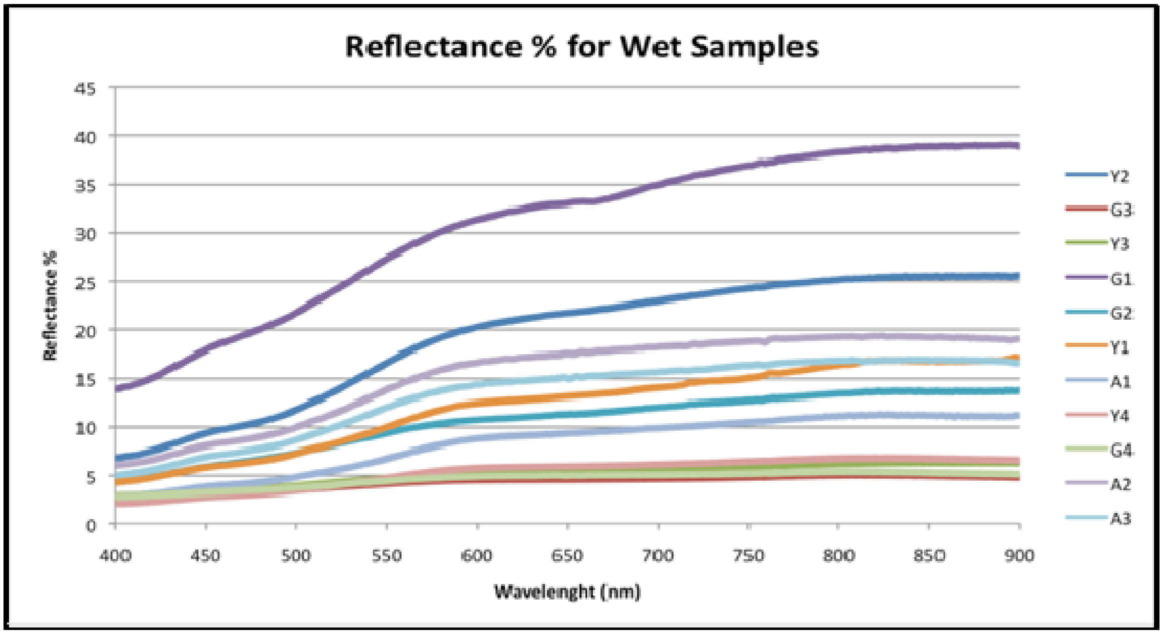


Figure 8: Example of XRD for G4 station, which shows quartz and halite.
Figure 5: X-Ray Diffraction for the Guanajibo River.

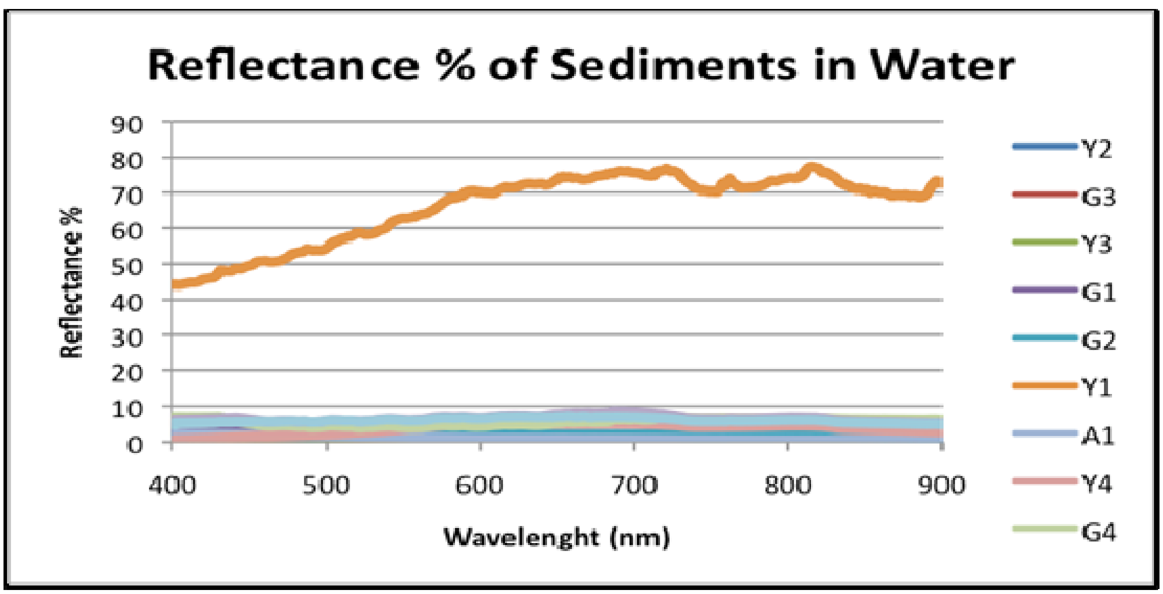
-*Spectral Response with the* GER-1500:



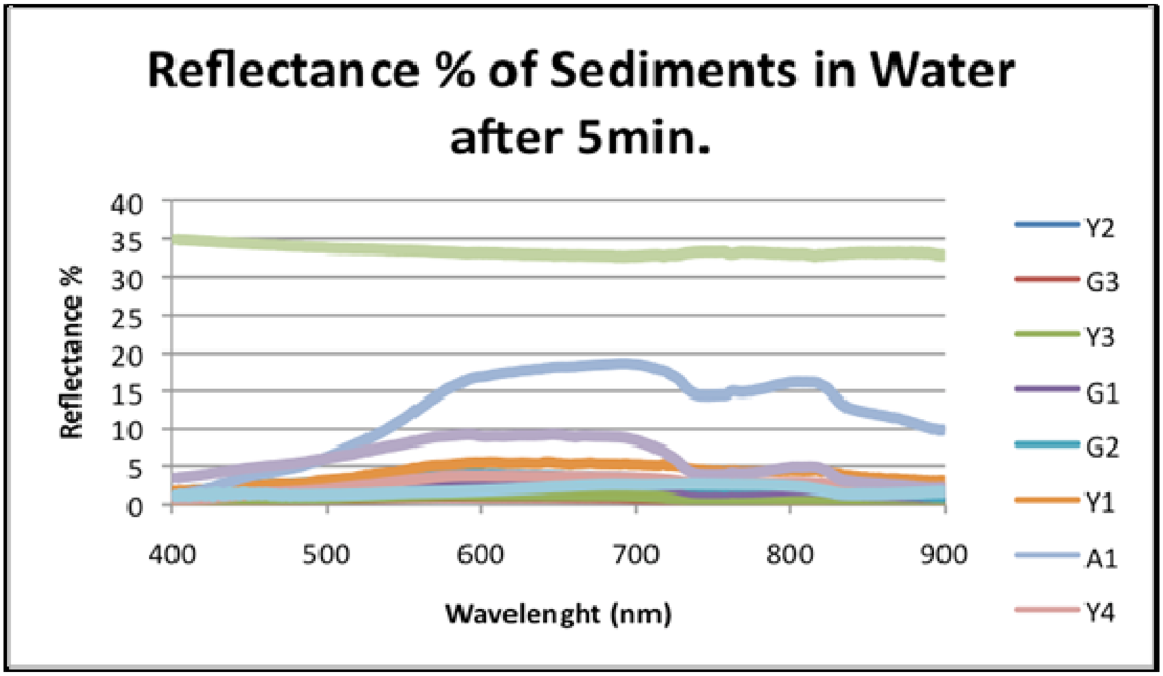
Graph 11: Reflectance curves for dry samples



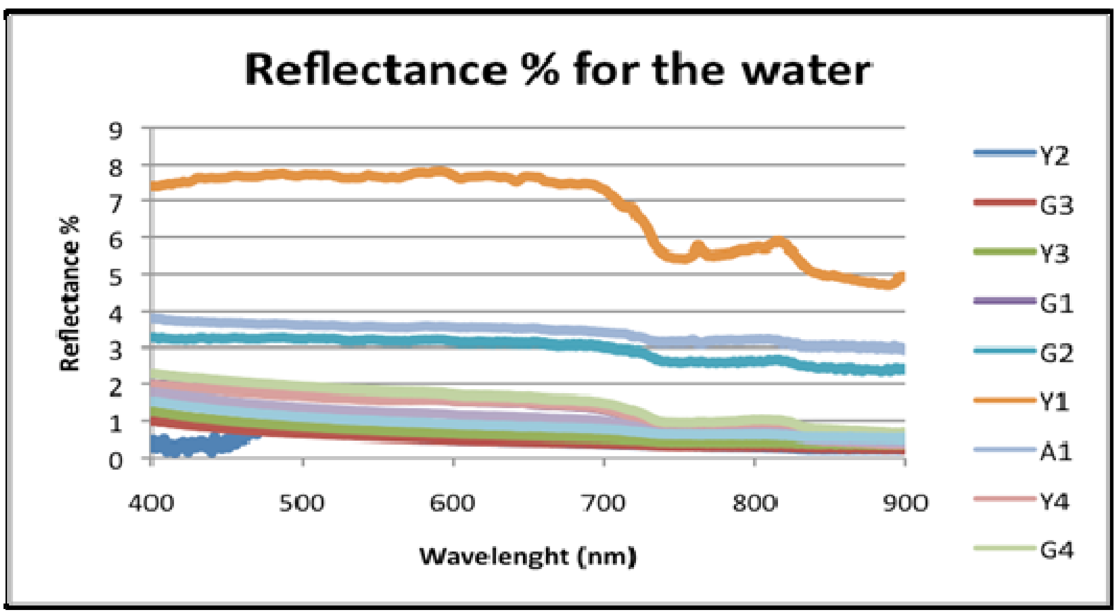
Graph 12: Reflectance curves for wet samples.



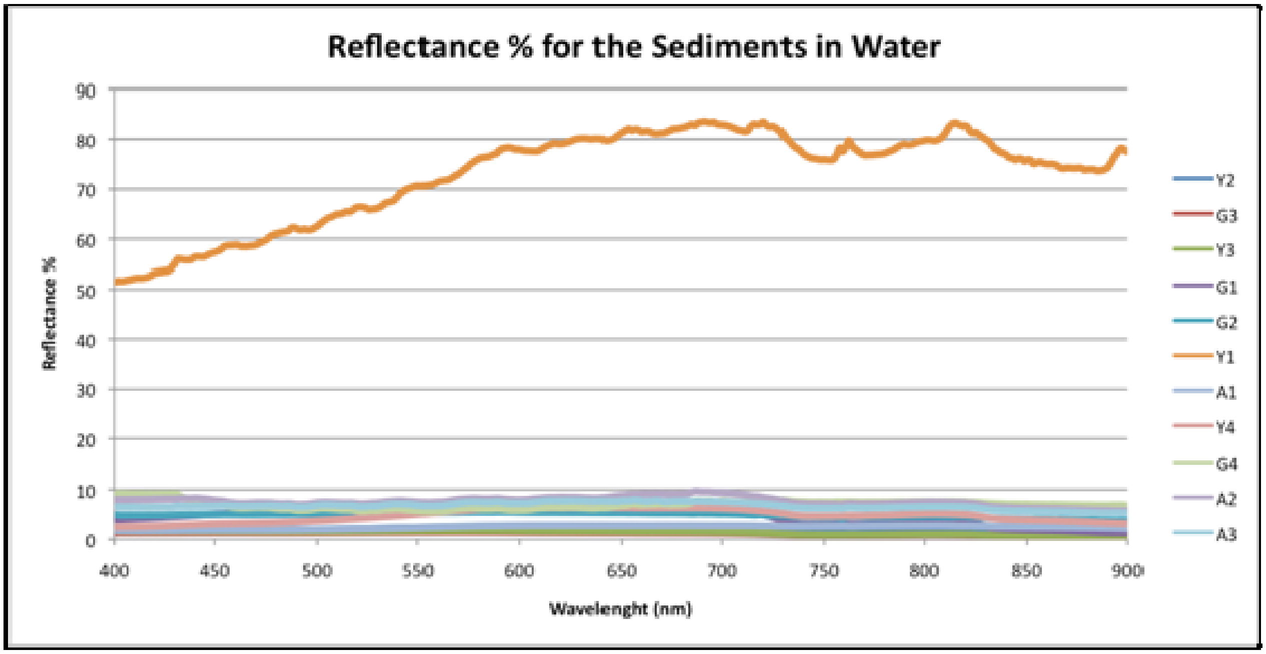
Graph 13: Reflectance curves for 7oz. of sample in water (these curves don't include the water reflectance).



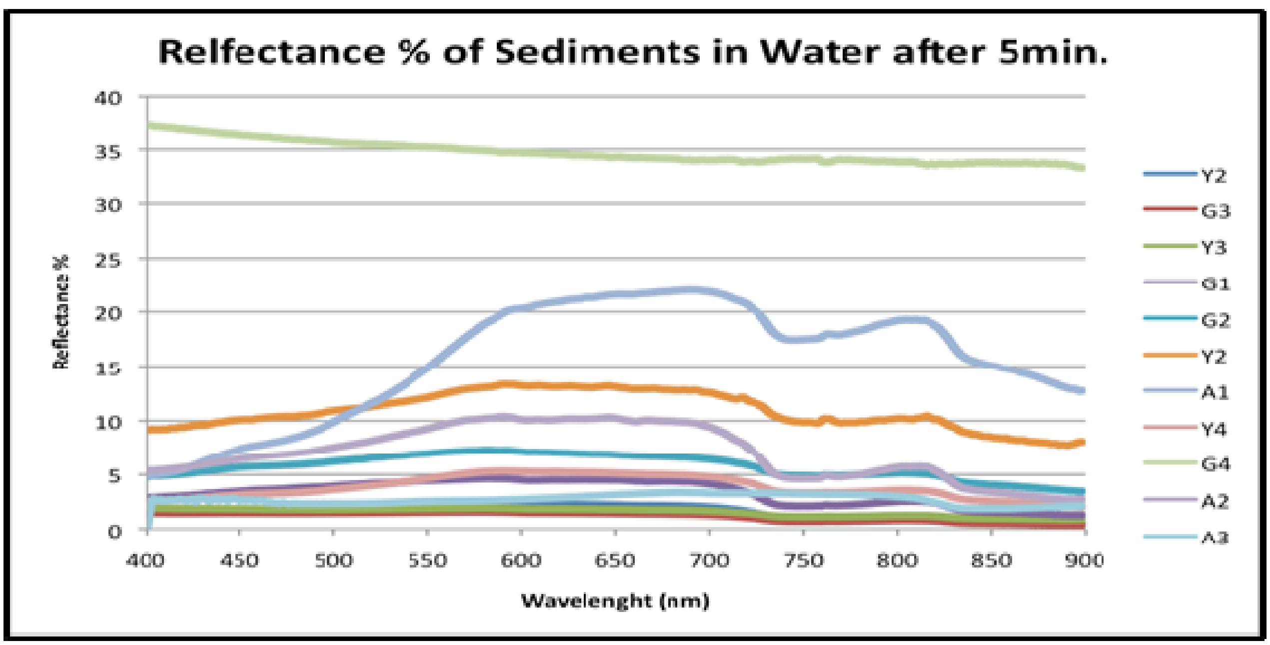
Graph 14: Reflectance curves for 7oz. of sample in water before 5 minutes (these curves don't include the water reflectance).



Graph 15: Reflectance curves for the water in which the sediments were added.

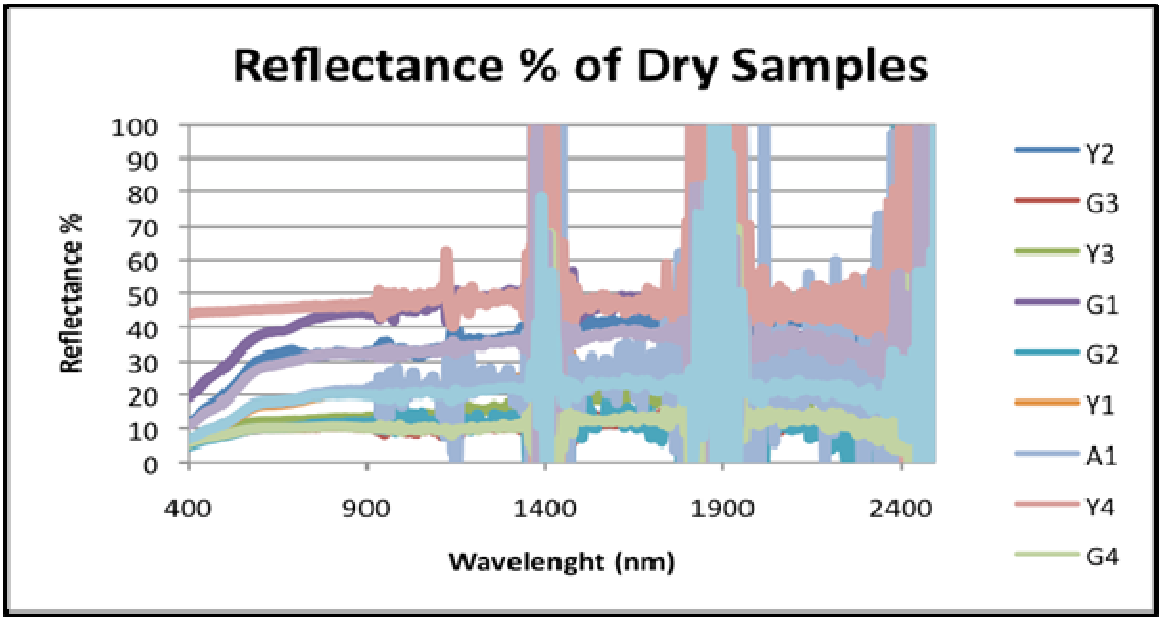


Graph 16: Reflectance curves for 7oz. of sample in water (these curves include the water reflectance).



Graph 17: Reflectance curves for 7oz. of sample in water before 5 minutes (these curves include the water reflectance).

Reflectance with the HR-1024:



Graph 18: Example of the reflectance curves obtained by the HR-1024 for dry samples.

IV. Discussion

The correlations values found in this study proved that the MODIS 1Km spatial resolution and the standard NASA algorithms for Chlorophyll are not appropriate for Mayagüez Bay.

Better correlations values were found for MODIS Terra, which cover the Mayagüez Bay during the morning. This has an important implication because of the amount of clouds and the atmospheric conditions of the area. Science Aqua passes the Bay in the afternoon the atmospheric conditions and the cloud cover increases and it makes more difficult to detect a good signal from a satellite sensor.

The correlation values of the suspended sediments and the chlorophyll-a from the MODIS sensor were also low, although for Terra we got a higher regression value. It was expected to find a good correlation with the suspended sediments because they have a big influence in the phytoplankton dynamics. For example, suspended sediments block the sunlight reaching the phytoplankton, which therefore reduces their production. More analyses are required to better understand the relationship between suspended sediments and Chlorophyll-a in Mayagüez Bay. Also, suspended sediments have a direct effect in the reflectance signal detected by satellite sensors, which also require more research.

After analyzing the results of the experiments, the values of all these tests shows that all the sediments deposited along the Bay have different characteristics. The grain size distribution demonstrates that the offshore stations have grains with lower diameter than the onshore samples. Also the grain size varies along the different rivers; on the Añasco River the grains are smaller then in the Yagüez and Guanajibo. The composition of the sediments depends on the localization and the sources. In Guanajibo River we have more terrigenous components than in Añasco and Yagüez and the lack of organic matter was evident in all the samples. The XRD, mineral composition, reveals that the quartz is present in almost all the stations, which is reasonable because it is one of the most resistant minerals. Also demonstrate that halite is present, it because the samples were collected in a marine environment and when the sample was dried the salt precipitate and forms halite. The relation between the reflectance curves and the minerals on the sample is because quartz is present in almost all the samples, this mineral tend to have a high magnitude in the reflectance curve on the visible range (Chiques, 2004). The grain size also affects the reflectance curve in the visible range. Decreasing the grain size, increase the number of mirrors off which the light reflects (Vincent 1997) hence finer material will reflect more. However observations of the different experiments, when comparing the effect of the mineral composition versus grain size over the reflectance curve, the mineral composition influence the reflectance more than grain size (Chiques, 2004). On this research the stations with finer grain sizes are A2, Y2 and G2, which reflects more than the others in the dry measures. The reflectance percent on the sample after 5min. of mix the water and 7oz of sediments the Y3 station reflects more than the others (30%), this station have 83% of 0.25Φ grain size.

VII. Conclusion

This project proved that MODIS 1Km spatial resolution does not work effectively in the Mayagüez Bay. This was proved by low correlations values for MODIS mounted in the two satellites. Also this project showed low relationship between suspended sediments and the phytoplankton chlorophyll-a, demonstrating the need of more research in this area.

After finish this study of the bottom sediments of the Mayagüez Bay, I can conclude that they are difference on the grain sizes along the rivers that affect the study area. Also they are a difference of composition, but the minerals, quartz and halite are present in almost all the samples. The spectral response of the samples, in the visible range, also varies. I can note that the samples of more percent of fine sediments reflect more on the dry measure than the coarser grains. On the measures of the simulation of re-suspension, the coarser grain stations reflect more than the fine sediments. The measures of due on the infrared range are not valid to due comparisons in this study because the values are wrong. This is due to the card use for reference in the measures that not is allowed to reflect on those wavelengths. Although the results on this study will help to future works on the study of the area of the Mayagüez Bay.

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Spectral Effects of Minerals in Sediments of Mayaguez Bay

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Abstract

This project is focus on the spectral response of minerals in suspended sediments of Mayaguez Bay. Rio Añasco, Yagüez and Guanajibo are the three major rivers that affect the sedimentation of Mayaguez Bay. Each river has three stations (Dentro, Boca and Playa) to obtain sediments and compare the spectral response of total suspended sediments (TSS) and without organic matter. Water samples were collected in September 21 and September 26, 2008. In the project, a laboratory procedure was developing to obtain pure minerals from the sediments and take out the organic material, which can affect the Remote Sensing Reflectance (Rrs). Rrs was obtained from data obtained using the GER-1500 radiospectrometer. In general, in the samples with minerals only, the value of Rrs is higher than in samples with TSS. The higher value of Rrs, in general, is related with high concentration of minerals. These results will help to develop other studies in Mayaguez Bay and will provide recommendations in remote sensing studies.

Key Words: suspended sediments, minerals, remote sensing reflectance, GER-1500 radiospectrometer, concentration, Mayaguez Bay

Puerto Rico has two major seasons that affect the precipitation: the rainy season (May to November) and the dry season (December to April). During these two seasons, the dynamics of suspended sediments in the Mayaguez Bay is affected (Hernandez, 2008). Mayaguez Bay is located in the west part of Puerto Rico at 18° 10' N and 18° 16' N of latitude and 67° 10' W and 67° 14' W of longitude (Figure 1). Mayagüez Bay has been studied for several years. Studies of the bay have included the dynamics of suspended sediments, optical properties, conditions of coral reefs, and others (Hernández, 2008, Quiñones, 2005, Rosado, 2000). During the rainy season, the Añasco, Yagüez and Guanajibo rivers have the highest discharge over the Mayaguez

Bay, and therefore that affect the concentration and dynamics of the sediments transported by these rivers and introduced into the bay (Gilbes et al., 1996). In September 21-24 of 2008, Puerto Rico was affected by a tropical wave that caused flood and mass wasting over the island. This was classified as an event of 200 years rainfall (R. Mojica, National Weather Service, San Juan, personal communication, October 2008). This event caused precipitation over 30 inches and large discharge in these rivers. Water samples from Rio Yagüez were collected in September 21, 2008, before the event, and water samples from Guanajibo and Añasco were collected in September 26, 2008, after the event. In each river the samples were collected in three stations: Dentro, Boca, and Playa. This project aimed to better understand the spectral effect of minerals in suspended sediments of Mayaguez Bay.

The main objective of this project was to determine the effect of total minerals in the spectral response of suspended sediments in Mayaguez Bay. This project is an effort for identifying the optical properties of minerals in suspended sediments, which will provide improvements and recommendations for remote sensing studies in coastal areas. In order to reach the main objective, the secondary objective of this work was to develop a laboratory procedure for determining the spectral response of total minerals in suspended sediments.

Water samples were filtered using pre-weighted Milipore HA 0.45 μm cellulose acetate membrane filters. Three replicates from each study site were obtained for comparison. All filters were heated at 70-80 ^{O}C during at least 6 hours to reduce water content before weighting. Water samples were filtered using pre-weighted Milipore HA 0.45 μm cellulose acetate membrane filters. Three replicates from each study site were obtained for comparison. All filters were heated at 70-80 ^{O}C during at least 6 hours to reduce water content before weighting. After pre-weighting, the filters were placed on the filtration system and using a vacuum machine, between 100 and 300 ml of water samples were filters. The filtrated volume depended on how much sediments were in the water. Filters were washed with plenty distilled water to remove salts from the filters. After this, the filters were removed and place in a dry chamber. The filters were heated again at 70-80 ^{O}C during at least 6 hours to remove residuals of water. After dry, the filters were placed in the dry chamber and weighted again. The concentration of total suspended sediments (TSS) was determined by the difference of weight between pre and post filtration. This concentration has two major potential errors: settling of the sediments in the plastic containers and contamination by salts. For that reason, the plastic containers were shaken very well and rinsed with plenty of distilled water. The non-mineral particles were removed using a standard commercial bleach. All filters were heated again at 70-80 ^{o}C during at least 4 hours to remove the bleach and get them ready for weighting again. A second set of reflectance measurements was taken. In this case it was expected to have in the filter only minerals. Reflectance of TSS was determined by measuring the sediments retained on the filters using the GER-1500 spectroradiometer. The measurements collected by the GER-1500 spectroradiometer were used to calculate the Remote Sensing Reflectance (Rrs) using the following equation:

$$Rrs = \frac{Lw}{Ed} \quad \text{Equation 1}$$

Lw=upwelling radiance, Ed=downwelling irradiance. The unit is *steradians^{-1}*.

Some Results are given in the next graphics.

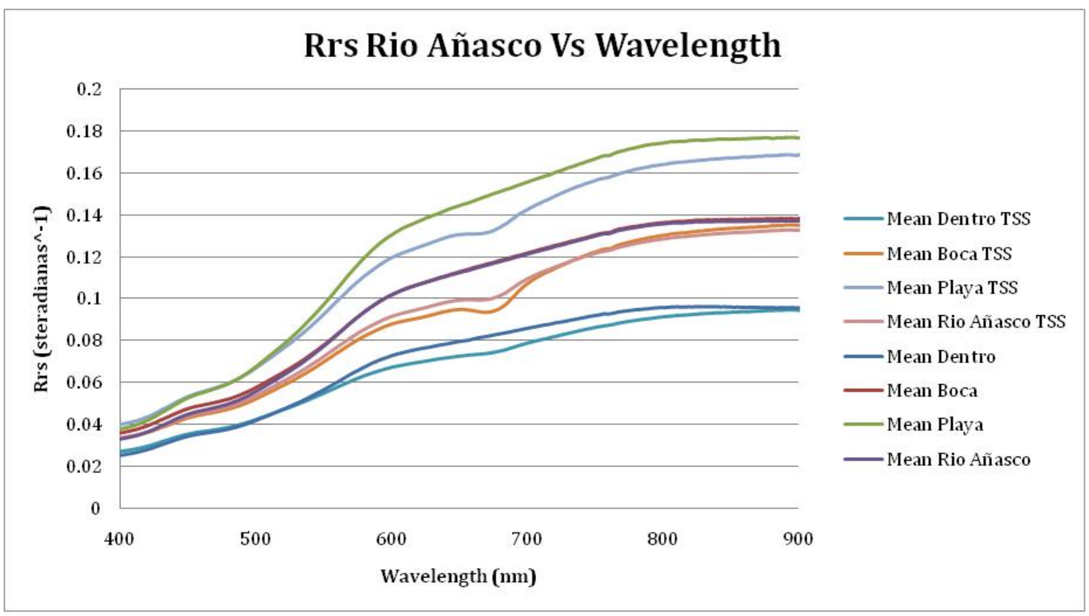

Figure 1 Rrs of Añasco River vs. Wavelength. The graphics that not have 'TSS' are graphics of inorganic matter.

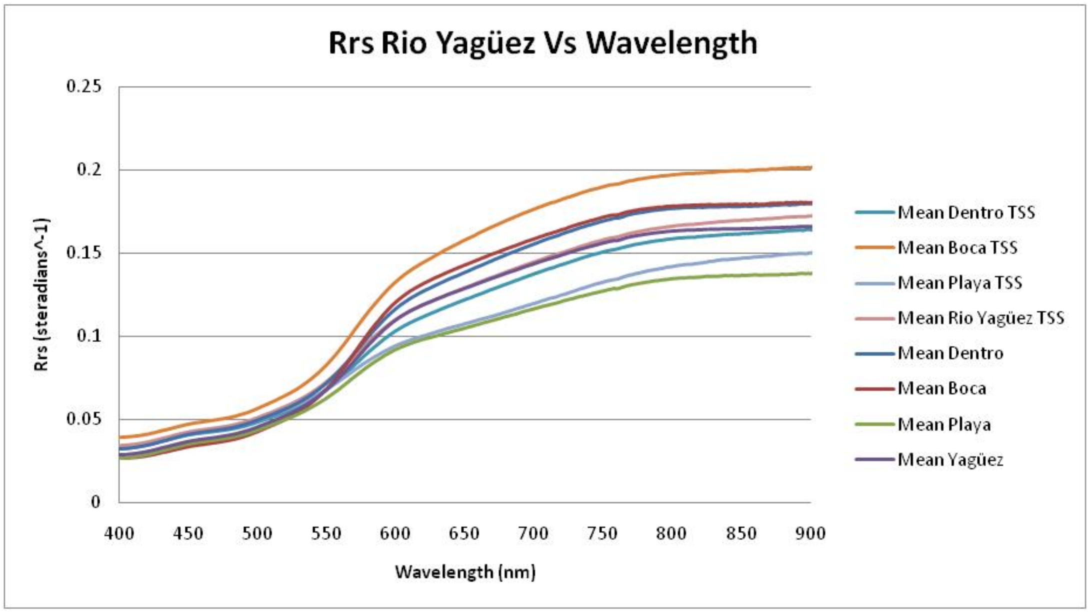

Figure 2 (below) Rrs of Yaguez River vs. Wavelength. The graphics that not have 'TSS' are graphics of inorganic matter.

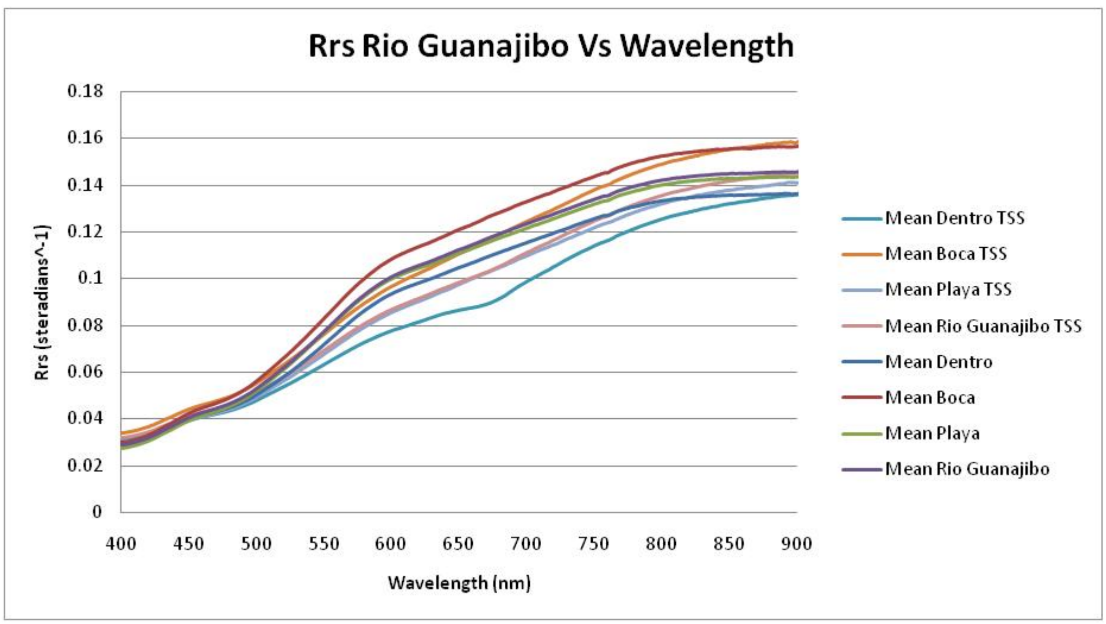

Figure 3 Rrs Guanajibo River vs. Wavelength.

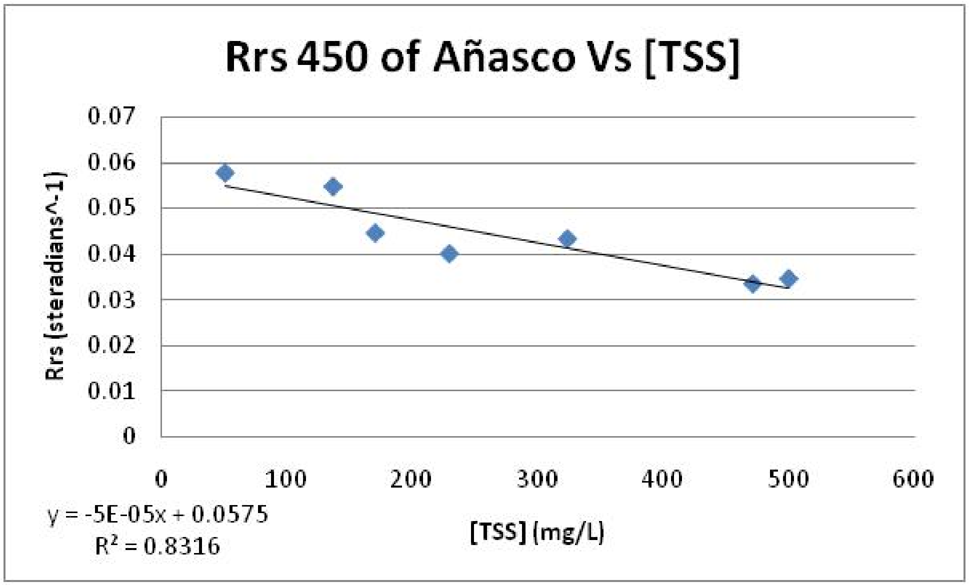

Figure 4 Regresion of Rrs on 450 nm of Añaco with TSS.

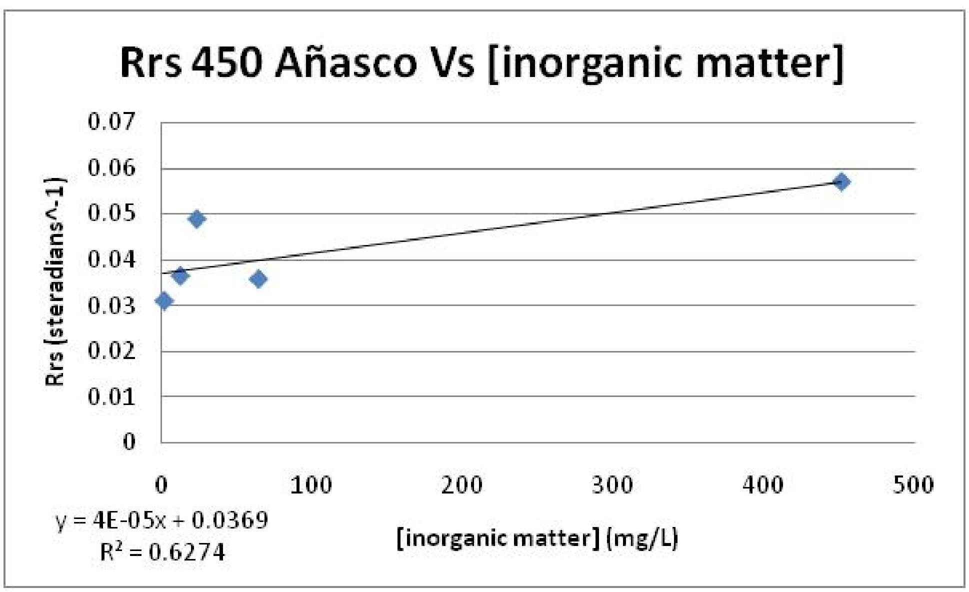

Figure 5 Regresion of Rrs on 450 nm of Añaco with Inorganic Matter (minerals).

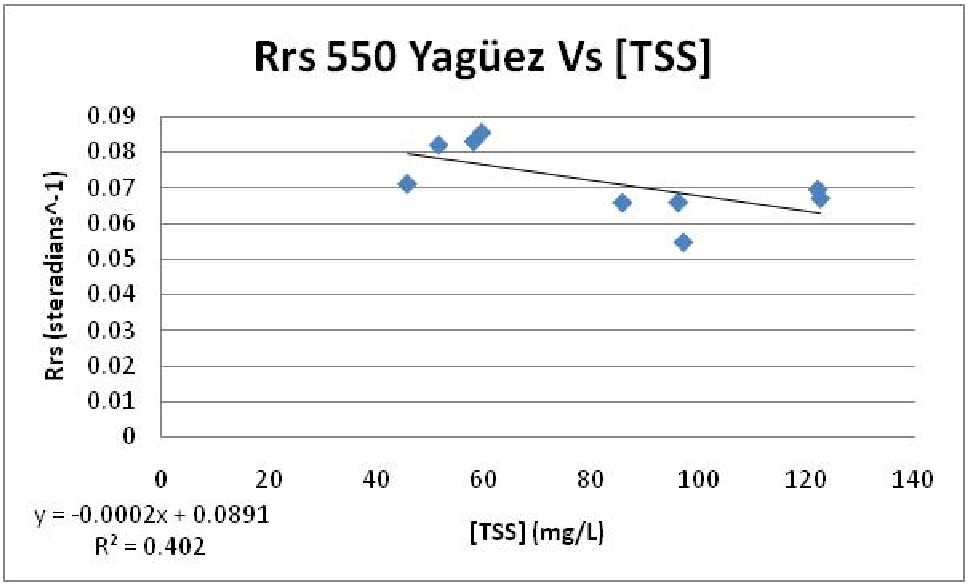

Figure 6 Regresion of Rrs on 550 nm of Yagüez with TSS.

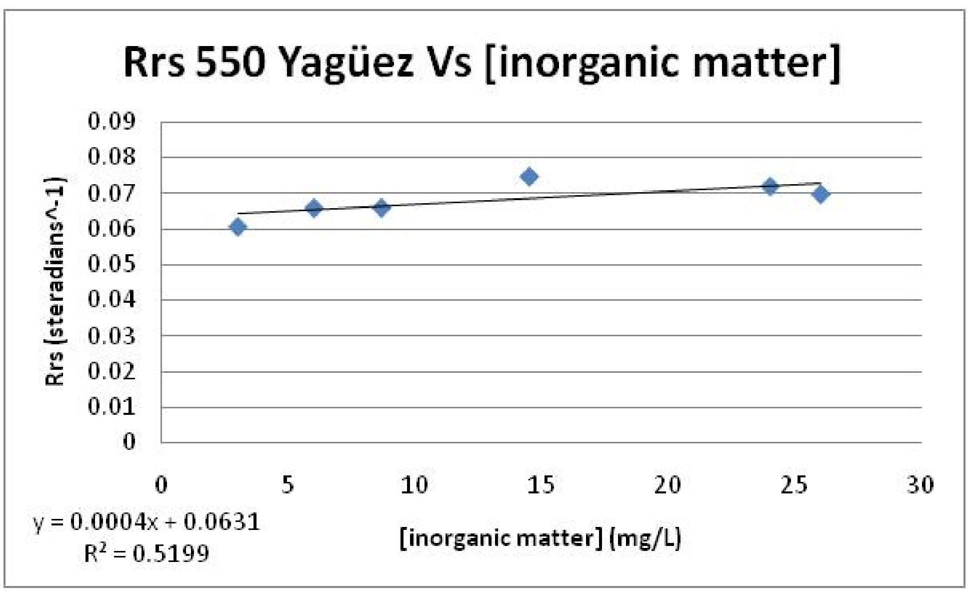

Figure 7 Regresion of Rrs on 550 nm of Añaco with Inorganic Matter (minerals).

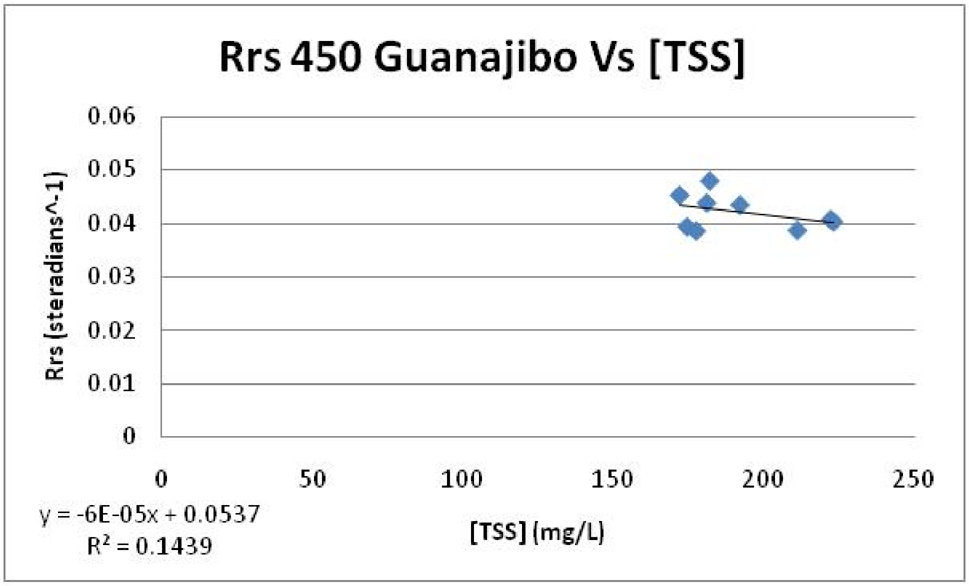

Figure 8 Regresion of Rrs on 450 nm of Guanajibo with TSS.

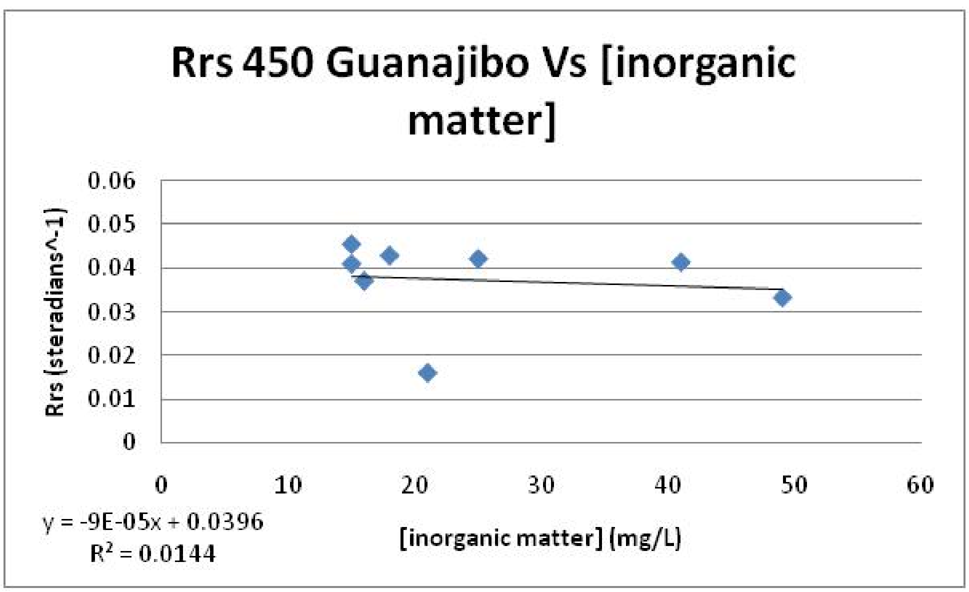

Figure 9 Regresion of Rrs on 450 nm of Guanajibo with Inorganic Matter (minerals).

Data collected in this study were affected by the high precipitation and discharge that occurred during September 21-24 in Puerto Rico. It was a unique event that produced extreme values of sediments concentration. A relation can establish that the Rrs in sediments for this project has a high value. Comparing Rrs data for each station before and after the removal of organic matter, the value of Rrs on Añasco with TSS was less than the Rrs with inorganic matter (minerals) only. A possible interpretation of this is that the organic matter reduces the spectral signal. In other words, it highly absorbs the radiation. Binding et al. (2007) establish that the organic matter may vary the absorption coefficient and affect the spectral signal. In this research, the organic matter may be the responsible for absorption of the radiation and affect the spectral signal that is received from the sediments. It looks like the minerals reflect more when are without organic matter. This was found in all the stations of Añasco and Guanajibo. In Rio Yagüez, only the station of Yagüez Dentro shows a higher value of Rrs with minerals than with TSS. The other two stations do not show it. This could be produced by the composition of minerals that are transported by Rio Yagüez, which may reflect less than those from the other rivers. Other possible reason is low concentration of organic matter in the sample, which produced very similar Rrs curves. Most of the differences in the Rrs curves were detected in the red and infrared regions of the spectrum. In general, Rrs at those wavelengths decreased with an increase in TSS concentration. After bleaching and have only minerals, the graphs of regression show that with high [inorganic matter] (or [only minerals]), the value of Rrs increase. The expectation was true, because in Froidefon et al. (2001) said that a high concentration of minerals induces a high value of Rrs. However, in Guanajibo stations show a high value of Rrs without organic matter, but when is compared with [inorganic matter], the values of Rrs decrease. This could be by the type of minerals that Rio Guanajibo transported, or the organic matter was not totally removed. In conclusion, the total suspended sediments showed lower values of Rrs that the sediments without organic matter. A higher concentration of organic matter makes that the Rrs decrease. However, a higher concentration of minerals makes a higher value of Rrs. For future research, the methodology must be improved and errors of weighting, the use of bleach and methods of calculations need to be changed. The next step in this research is to identify the minerals that are in the suspended sediments of each one of the rivers. Reprocess and new analyses of the collected data will also be necessary

Remote Sensing of Coastal Waters Progress report
Development of the GERSview Data portal

Ramon Lopez UPRM-Marine Sciences Department

Overview

My contribution to the Mayaguez bay project for the September through December 2008 period included the conclusion of the web based data portal (briefly described below), the analysis of existent radiometric data, and the orientation of laboratory mates on the procedure to construct the data portal projects. This period also include the ending of my dissertation final draft, the defense and the submission to graduate school of the final document.

Dissertation completion and defense

During the last semester of 2008 I submitted my last draft to my graduate committee. Once the draft was approved the final document was presented to graduate school during the month of October. The presentation and defense of the document took place on November 26, 2008 and the final corrected document was approved and submitted graduate school during the month of December. A copy of the approved dissertation can be accessed through the following address http://grad.uprm.edu/tesis/lopezrosado.pdf .

The Web based data portal

The existent laboratory optical and biogeochemical data is been share with the general public and scientific community through a web based data portal, using the Web Map Server ARCIMS. This map server provided the means to serve maps across the internet in a similar arrangement as it would by a GIS desktop tool. This allowed the layers of the Mayaguez bay to be overlapped and be related to the different ancillary parameters that were included in the ARCMAP project. Figure 1 shows a screen shot of one of the published pages. The web address to the portal is http://gersview.uprm.edu. Besides the user being able to visually analyze the layer interactions it will be possible to access the data that originated them.

Radiometric data analysis

Radiometric data is available for the Mayaguez bay project sampled days since 2001(Table 1). This data set includes irradiance and radiance measurements profiles of each sampled station (Figure 2). The first step in its analysis was the organization and filtering of these stations profiles, once step one was accomplish the next step was to derived diffuse attenuation coefficient (K_d) profiles to analyze behavior of the light field as its affected by the river plumes of the area (Figure 3). This analysis is still in process and will be completed by the remaining NOAA Crest students of the lab. Once completed, the surface K_d will be used to create GIS layers for ARCMAP projects, this new data will be then added to the existent web based portal. In addition GIS layers of remote sensing reflectance will also be included in these new ARCMAP projects. When these tasks are completed the web based data portal will include an extensive array of parameters that span from the biochemical properties to the biogeo-optical properties of the Mayaguez bay.

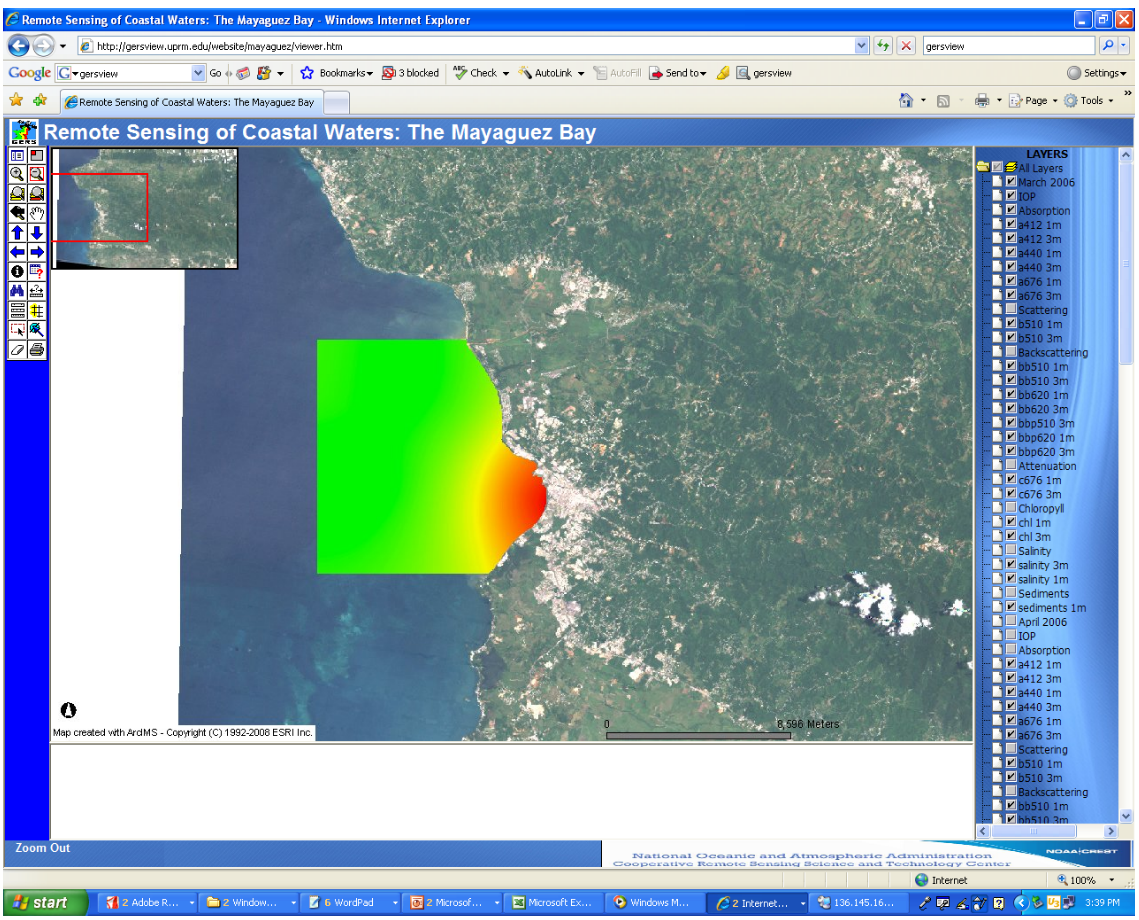

Figure 1 Screen shot of a published data set through the http://gersview.uprm.edu data portal.

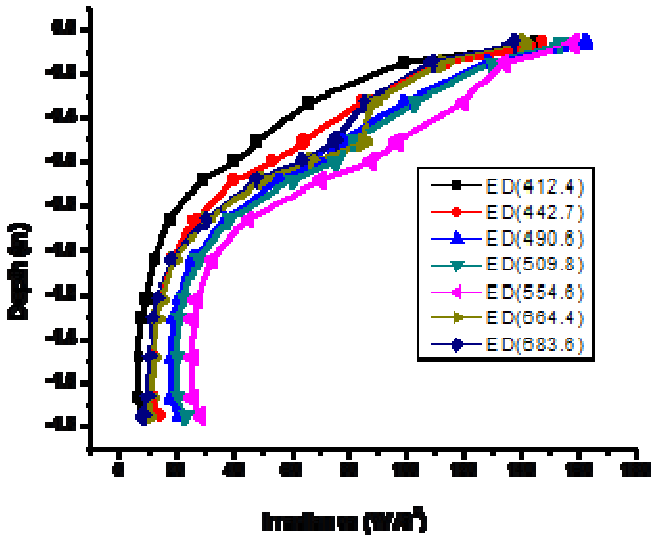

Figure 2 Example of downward irradiance at the Añasco station 1 during the sampling of April 2006.

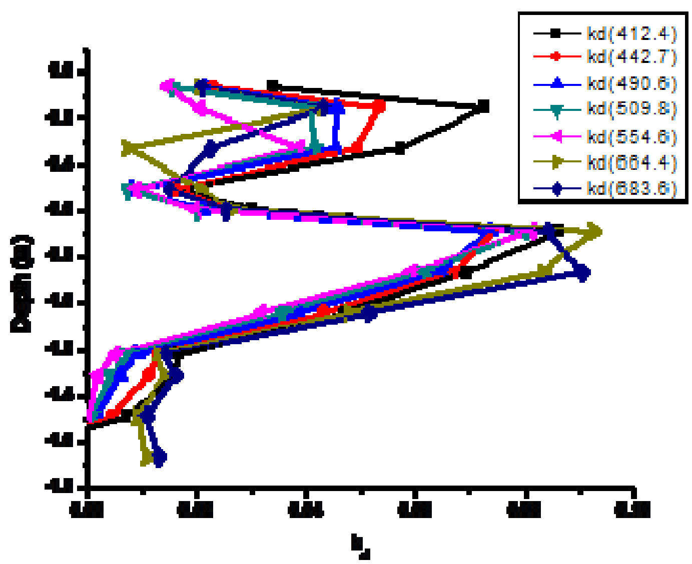

Figure 3 Example of diffuse attenuation coefficient profile at Añasco station 1 during the sampling of April 2006.

Table 1 Available data sets for the cruises to the Bay Mayaguez

Sampled Months										
Apr-01	Oct-01	Feb-02	Aug-02	Feb-03	Oct-03	Jan-04	Feb-04	Aug-04	Mar-05	Jul-05
Aug-05	Sep-05	Oct-05	Dec-05	Mar-06	Apr-06	Sep-06	Oct-06	May-07	Mar-08	

Presentations at Scientific meetings

November 14, 2008. Sixth meeting on Remote Sensing and Geographic Information Systems (PRYSIG, for Spanish) held at University of Puerto Rico at Mayaguez

Presentation: **Remote Sensing and Bio-optical Properties of the Mayaguez bay**
By Ramon Lopez Rosado and Vilmaliz Rodriguez Guzman
http://gers.uprm.edu/pdfs/pres_lopez_rodriguez.pdf

November 26, 2008. Doctoral dissertation presentation and defense

Presentation: **Photosynthetic Efficiency of Phototrophic Plankton and Bio-Optical Variability as Influenced By Mesoscale Processes in the Eastern Caribbean Basin.**

COASTAL –GILBES' GROUP REPORT

(Performance period: March 1, 2009 to August 31, 2009)

RESEARCH COMPONENT

RESEARCH PROJECT SUMMARY FOR THE REPORTING PERIOD ONLY

Project	Tasks	CREST Researcher	Students involved	NOAA and Other Colloborators
Project (2) Field measurements in coastal waters for algorithm testing/development and satellite validation.	Compare to satellite water leaving products and atmosphere retrievals. Intercomparison of the below/ above water signals with aircraft and satellite data as available.	F. Gilbes	Vilmaliz Rodriguez (M.S. Student) Natlee Hernández (M.S. Student)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Eric Harmsen Roy Armstrong From CSU: Carlos Ramos-Scharrón
Project (3) Improvement/ Development of algorithms for remote sensing of coastal waters.	Analysis of optical field measurement together with Chl, TSS concentrations. Evolution and tuning of algorithm for Chl retrieval in PR coastal waters. Development of GIS database for land sea interactions in Mayaguez Bay.	F. Gilbes	Vilmaliz Rodriguez (M.S. Student) Natlee Hernández (M.S. Student) Alexis Cruz (B.S. Student graduated in May 2009, now M.S. Student)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Eric Harmsen Luis Pérez-Alegría Roy Armstrong From CSU: Carlos Ramos-Scharrón

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation
Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.

- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.

- **Supervising PI or Co-Is:** Fernando Gilbes Santaella

- **Publications (during performance period):**
  -Journal Publications with Students:
  - Rodríguez-Guzmán, V., F. Gilbes-Santaella (2009) Estimating Total Suspended Sediments in Tropical Open Bay Conditions using MODIS. In: Proceedings of the 8th WSEAS International Conference on Instrumentation, Measurement, Circuits and Systems, Hangzhou, China, May 20-22, 2009, pp 83-86. http://gers.uprm.edu/pdfs/rodriguez_gilbes_09a.pdf
  - Rodríguez-Guzmán, V., F. Gilbes-Santaella (2009) Using MODIS 250 m Imagery to Estimate Total Suspended Sediment in a Tropical Open Bay. International Journal of Systems Applications, Engineering & Development. 3(1):36-44. http://gers.uprm.edu/pdfs/rodriguez_gilbes_09b.pdf

  -On-line Publications:
  - Cruz-Benitez, Alexis (2008) Spectral Effect of Minerals in Sediments of Mayagüez Bay, 34 pages. http://gers.uprm.edu/pdfs/topico_alexis2.pdf

  -Books:
  - Fernando Gilbes and students have continued working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published

in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM and the University of Puerto Rico Press.

- **Dollar amount of funds leveraged with CREST funds (during performance period):**

Project Title	Sponsoring Agency	PI/Co-PI/ Recipient/Group	Dollars	Start Date	End Date
Study of Benthic Habitats Using Hyperspectral Remote Sensing	NSF-CenSSIS	PI: Miguel Velez Co-PI: Fernando Gilbes among others	$50,000	March 2000	February 2010
Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands	University of Puerto Rico Sea Grant College	PI: Johannes Schelekens Co-PI: Fernando Gilbes	$30,000	June 2006	December 2009

- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** None
- **Students MS:** Vilmaliz Rodriguez and Nathlee Hernández, UPRM-Dep. Of Geology
- **Students Undergraduate:** Alexis Cruz, UPRM-Department of Geology (this student worked in a NOAA CREST related topic, but he was not directly funded by the project)
- **NOAA Collaborators:** A site-specific algorithm has been developed and tested to estimate Total Suspended Sediments (TSS) in Mayaguez Bay. This algorithm is being incorporated in NOAA-NESDIS system as a "testing product" of TSS for Puerto Rico in collaboration with Joaquin Trinanes, Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node.
- **Other Collaborators:** Eric Harmsen (UPRM-Department of Agricultural Engineering), Carlos Ramos-Scharrón (Department of Geosciences, Colorado State University), and Roy Armstrong (UPRM-Department of Marine Sciences).
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Processing of field data collected in Mayaguez Bay over the past eight years was continued. A third version of a site-specific algorithm for the estimation of Total Suspended Sediments in Puerto Rica coastal waters has been developed and its implementation as "testing product of the NOAA CoastWatch program is underway. Remote sensing reflectance measurements obtained with the GER-1500

spectroradiometer are being used to estimate these parameters and compared with MODIS data. Several experiments were conducted to better understand the effect of suspended sediments on the remote sensing reflectance. Additional biogeo-optical data have been incorporated in GERSVIEW (the on-line GIS-database of the GERS Lab) for further analyses and comparisons with satellite data. Good progress has been obtained in all proposed tasks.

Tasks (For year III as per the Milestone Chart)

Task: Compare to satellite water leaving products and atmosphere retrievals

Evaluation of MODIS data continues to fine-tuning the algorithm to estimate total suspended sediments (TSS). Two image processing methods, based on two image analysis packages predefined routines (i.e. ENVI and SeaDAS), were evaluated and compared in order to determine the most suitable method for this purpose. Developed algorithms were evaluated by applying resultant equations to two MODIS images from which in situ data were available. Analyses with the GIS based model continued to estimate sediment load to the Mayagüez bay and compare it with same estimations derived from MODIS data. This model is based on the Revised Universal Soil Loss Equation (RUSLE), which requires to spatially defining a series of factors that promotes soil erosion. Basic information, such as Land Use, soil series and annual precipitation, was used to define these factors. New results confirmed that the resultant values are reasonable when compare to previous studies and their spatial distribution responded to known characteristics of the area. This work is part of Vilmaliz Rodriguez master theses.

Task: Intercomparison of below/above water signals with aircraft and satellite data as available.

As discussed in previous reports, we have found that characteristics of the sediments, like composition and grain size distribution, have important implications in the optical properties of the water. We continue addressing this issue as demonstrated in the work by undergraduate student Alexis Cruz and recent-hired graduate student Natlee Hernandez. Both students compared reflectance measurements with sediments composition. Four different techniques for mineral composition were evaluated and tested: X-Ray Diffraction (XRD), Spectroscopy, Inductively coupled plasma mass spectroscopy (ICP-MS), and Scanning Electron Microscope (SEM). The data collected by these techniques are now being analyzed and next report will have a more comprehensive results and conclusions about the effect of mineral composition in the spectral response of suspended sediments.

Task: Analysis of optical field measurement together with Chl, TSS concentrations

This task is focused on the spectral response of minerals in suspended sediments of Mayaguez Bay. Rio Añasco, Yagüez and Guanajibo are the three major rivers that affect the sedimentation of Mayaguez Bay. Each river had three stations (Dentro, Boca and Playa) to obtain sediments and compare the spectral slope of total suspended sediments (TSS) and without organic matter. Water samples were collected in September 21 and September 26, 2008. A laboratory procedure was developed to obtain pure minerals from the sediments and take out the organic material, which can affect the Remote Sensing Reflectance (Rrs). Rrs was obtained using the GER-1500 spectroradiometer. Differences in the spectral slope were found along the study sites demonstrating that mineral composition play an important role in the development of future remote sensing techniques for estimations of suspended sediments. More details of this task can be found in Alexis Cruz report (http://gers.uprm.edu/pdfs/topico_alexis2.pdf).

Task: Evolution and tuning of algorithm for Chl retrieval in PR coastal waters

After several years working with this task and based on the results presented in the dissertation of Marcos Rosado (http://gers.uprm.edu/pdfs/thesis2_marcos.pdf) it has been demonstrated that the estimation of chlorophyll a (Chl-a) using current ocean color sensors is impossible for Mayaguez Bay. Neither SeaWiFS nor MODIS are capable to generate reliable estimates of Chl-a because of their spatial resolutions and corresponding bio-optical algorithms. The diverse efforts for developing a site-specific algorithm for estimation of Chl-a has also been unsuccessful because the lack of good quality images and the strong effect of coastal processes over the optical signal detected by these remote sensors. Therefore, it has been decided to stop working with this task and get focus on improving the estimation of suspended sediments by ocean color sensors. This has a larger potential of success. Based on this decision future reports will not include a narrative of this task.

Task: Development of GIS database for land sea interactions in Mayaguez Bay

Quality control of all data collected in Mayaguez Bay was continued during the reported period. In addition, new analyses of the collected radiometric data were started. This data set was not included during the first round of processing because the nature of processing and quality control is more complicated and requires particular attention. Transfer of knowledge between Ramon Lopez (Ph.D. student graduated in Dec 08) and Natlee Hernandez (new M.S. student) continued in order to further development of GERSVIEW.

Future Tasks (From the Milestones)

Efforts for developing site-specific algorithms for suspended sediments will continue. Other optical data are being organized and they are getting ready for the GIS databases. Very soon they will be exported to ArcIMS and be published in the web. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay. Natlee Hernandez (new M.S. student), will continue working with this important aspect of the project. Another publication by Vilmaliz Rodriguez will be submitted to a peer-review journal before the end of the year. She will also defend her master thesis. The PI and other students will continue working with the chapters of the Mayaguez Bay book.

Appendix: The following links include publications related with work of this report period.

http://gers.uprm.edu/pdfs/rodriguez_gilbes_09a.pdf

http://gers.uprm.edu/pdfs/rodriguez_gilbes_09b.pdf

http://gers.uprm.edu/pdfs/topico_alexis2.pdf

http://gers.uprm.edu/pdfs/thesis2_marcos.pdf

COASTAL –GILBES' GROUP REPORT
(Performance period: September 1, 2009 to February 28, 2010)

RESEARCH COMPONENT

RESEARCH PROJECT SUMMARY FOR THE REPORTING PERIOD ONLY

Project	Tasks	CREST Researcher	Students involved	NOAA and Other Colloborators
Project (2) Field measurements in coastal waters for algorithm testing/development and satellite validation.	Compare to satellite water leaving products and atmosphere retrievals. Inter-comparison of the below/ above water signals with aircraft and satellite data as available.	F. Gilbes	Vilmaliz Rodriguez (M.S. Student) Natlee Hernández (M.S. Student)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Eric Harmsen Roy Armstrong From CSU: Carlos Ramos-Scharrón
Project (3) Improvement/ Development of algorithms for remote sensing of coastal waters.	Analysis of optical field measurement together with Chl, TSS concentrations. Development of GIS database for land sea interactions in Mayaguez Bay. Development of GIS model for land-sea interactions in Mayaguez Bay.	F. Gilbes	Vilmaliz Rodriguez (M.S. Student) Natlee Hernández (M.S. Student)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Eric Harmsen Luis Pérez-Alegría Roy Armstrong From CSU: Carlos Ramos-Scharrón

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation
Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.

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- **Supervising PI or Co-Is:** Fernando Gilbes Santaella

- **Publications (during performance period):**

  -Thesis Publication:
  - Rodríguez-Guzmán, Vilmaliz (2009) Remote Sensing of Suspended Sediment in Mayagüez Bay Associated with Inland Soil Erosion Rates. University of Puerto Rico at Mayaguez, Department of Geology, 123 pages. http://gers.uprm.edu/pdfs/thesis_vilmaliz.pdf

  -Book:
  - Fernando Gilbes and students have continued working with their chapters for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM and the University of Puerto Rico Press.

- **Dollar amount of funds leveraged with CREST funds (during performance period):**

Project Title	Sponsoring Agency	PI/Co-PI/ Recipient/Group	Dollars	Start Date	End Date
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Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands	University of Puerto Rico Sea Grant College	PI: Johannes Schelekens Co-PI: Fernando Gilbes	$30,000 (No cost extension)	June 2006	May 2010

- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** None
- **Students MS:** Vilmaliz Rodriguez and Natlee Hernandez, UPRM-Dep. Of Geology
- **Students Undergraduate:** None
- **NOAA Collaborators:** A site-specific algorithm has been developed and tested to estimate Total Suspended Sediments (TSS) in Mayaguez Bay. This algorithm is being incorporated in NOAA-NESDIS system as a "testing product" of TSS for Puerto Rico in collaboration with Joaquin Trinanes, Acting NOAA Coast Watch Operations Manager for the Caribbean Regional Node.
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- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Vilmaliz Rodriguez successfully defended her thesis on December 8, 2009. This work was fully funded by NOAA-CREST and covered several tasks of this thrust. A site-specific algorithm for the estimation of Total Suspended Sediments in Puerto Rico coastal waters was developed and its implementation as "testing product of the NOAA CoastWatch program is underway. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer were used to estimate this parameter and compared with MODIS data. Her work also helped to create the on-line GIS-database of the GERS Lab (GERSVIEW) and to evaluate a model for land-sea interface studies. A new effort by Natlee Hernandez is now in progress to better understand the effect of suspended sediments on the remote sensing reflectance. Good progress has been obtained in all proposed tasks.

Tasks (For year IV as per the Milestone Chart)

Task: Compare to satellite water leaving products and atmosphere retrievals

In situ measurements of total suspended sediments (TSS), backscattering (bb and bbp), Remote Sensing reflectance (Rrs), and MODIS-Terra band 1 reflectance were spatially and temporally compared. Spatial analyses indicated that absolute values of TSS, Rrs and bb increases with proximity to shoreline. It was observed that median values of bb and bbp vary spectrally, and higher difference in magnitude between these parameters was observed in shorter wavelengths and offshore stations. Good relationships resulted from TSS concentration and bbp linear regression analyses in all six analyzed wavelengths (R2=0.74-0.76; n=133). Resultant correlation results between bb and Rrs using corresponding wavelength, show significant wavelength dependant variations where best relationship was observed at 620 nm (R2=0.78; n=61). The relationship between Rrs and TSS indicate that the best wavelengths to estimate TSS are between 589 to 645 nm. The analysis of Rrs single band and Rrs ratio for derivation of TSS indicates that red to green ratio (Rrs655/Rrs545) present the best correlation results (R2=0.84; n=72). Simultaneous MODIS reflectance band 1 data and *in situ* measurements of TSS concentration, bbp620 and Rrs645 were all positively correlated, but more data are required to better define and validate the results. Sensors with better spatial and spectral resolution are needed in order to generate operational products of TSS in these highly variable optical tropical waters. This work is part of Vilmaliz Rodriguez master theses.

Task: Intercomparison of below/above water signals with aircraft and satellite data as available.
Monitoring and better understanding of sediment flux and processes in coastal environments are important to maintain water quality and geomorphologic balance. Development and validation of an algorithm to estimate total suspended sediment (TSS) was performed based on *in situ* remote sensing reflectance (Rrs) and MODIS/Terra band 1 data. Two image processing methods, based on two image analysis packages with predefined routines, were evaluated and compared in order to determine the most suitable method for the study area. Analyses of *in situ* data showed a significant relationship between TSS and *in situ* Rrs at 645 nm (R2=0.73) indicating positive response of this parameter in the interested region of the spectrum. Developed algorithms were evaluated by applying resultant equations to two MODIS images from which *in situ* data were available. In the validation analysis the lower error was encountered when using an exponential equation, however linear equations estimations followed better the tendency of measured values. TSS estimations of all three algorithms presented values within the range of *in situ* observations and spatial patterns characteristic of coastal environments. Additional data and pre-processing parameters should be evaluated in order to improve validation results and produce TSS operational products for tropical coastal waters. This work is part of Vilmaliz Rodriguez master theses.

Task: Analysis of optical field measurement together with Chl, TSS concentrations
A new effort has started in order to understand how the sediments of the Añasco, Yagüez and Guanajibo rivers affect the optical signal of Mayagüez Bay. The planed work is based on recent findings by Vilmaliz Rodriguez and it will be performed by Natlee Hernandez. Remotely sensed and *in-situ* measurements are going to be used. Determination Physical and geological characteristics of the suspended sediments will help us to understand the behavior of the spectral responses. The XRD and the Sedigraph 5100 instruments will be used to determine the mineral composition and the grain sizes. The MERIS ocean color sensor from the ESA (European Spatial Agency) data will be compared to in-situ measurements. Finally, all the data will be associated to the season in which was collected and correlated to the physical characteristics of the particles. During this semester field work and laboratory analyses will begin by Natlee.

Task: Development of GIS database for land sea interactions in Mayaguez Bay
Quality control of all data collected in Mayaguez Bay was continued during the reported period. In addition, new analyses of the collected radiometric data were started. This data set was not included during the first round of processing because the nature of processing and quality control is more complicated and requires particular attention. Transfer of knowledge between Vilmaliz Rodriguez and Natlee Hernandez continued in order to further develop the GERSVIEW database.

Task: Development of GIS model for land-sea interactions in Mayaguez Bay.
The Revised Universal Soil Loss Equation (RUSLE) was applied to Mayagüez Bay watershed by defining raster layers (pixel size = 10 m) of associated factors in a GIS based model. Spatially variable soil erosion rates and sediment yields estimations, from 2001 to 2005, were estimated for this basin. Validation results indicated that the equation published by Boyce (1975) to calculate sediment delivery ratios (SDR) responded to conditions of the area, while the other two equations evaluated for the same purposes (Vanoni, 1975 and USDA, 1972) tended to overestimate this parameter. Sediment yield estimations generated for year 2004 for Rosario river sub-watershed (32,365 Mg/yr) were highly comparable to field measurements at USGS gauge station (33,622 Mg/yr) showing the great potential of the developed model. MODIS data for twenty dates of 2004 were used to generate suspended sediment load products corresponding to northern and southern parts of the bay. Results of the northern area showed a fairly good relationship (R2=0.71) with Añasco river discharge measurements, but additional values of high river discharge are required to strengthen this association. This work is part of Vilmaliz Rodriguez master theses.

Future Tasks (From the Milestones)
Efforts for developing site-specific algorithms for suspended sediments will continue. This will include a better understanding of the physical and geological characteristics of sediments. Other optical data are being organized and they are getting ready for the GIS databases. Very soon they will be exported to ArcIMS and be published in the web. This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in Mayaguez Bay. Natlee Hernandez (new M.S. student), will continue working with this important aspect of the project. Another publication by Vilmaliz Rodriguez will be submitted to a peer-review journal very soon. The PI and other students will continue working with the chapters of the Mayaguez Bay book.

Appendix: The following links include publications related with work of this report period.

http://gers.uprm.edu/pdfs/thesis_vilmaliz.pdf

http://gers.uprm.edu/pdfs/report_natlee_feb10.pdf

COASTAL –GILBES' GROUP REPORT
(Performance period: March 1, 2010 to August 31, 2010)

RESEARCH COMPONENT

RESEARCH PROJECT SUMMARY FOR THE REPORTING PERIOD ONLY

Project	Tasks	CREST Researcher	Students involved	NOAA and Other Colloborators
Project (2) Field measurements in coastal waters for algorithm testing/development and satellite validation.	Compare to satellite water leaving products and atmosphere retrievals. Inter-comparison of the below/ above water signals with aircraft and satellite data as available.	F. Gilbes	Natlee Hernández (M.S. Student)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Roy Armstrong
Project (3) Improvement/ Development of algorithms for remote sensing of coastal waters.	Analysis of optical field measurement together with Chl, TSS concentrations. Development of GIS database for land sea interactions in Mayaguez Bay. Development of GIS model for land-sea interactions in Mayaguez Bay.	F. Gilbes	Natlee Hernández (M.S. Student)	Joaquín Trinanes (Acting NOAA CoastWatch Operations Manager for the Caribbean Regional Node) From UPRM: Roy Armstrong

Thrust: Remote Sensing of Coastal Waters

Project 2: Field measurements in coastal waters for algorithm testing/development and satellite validation
Project 3: Improvement/Development of algorithms for remote sensing of coastal waters

- **Relevance to NOAA's mission and the strategic plan:** This project is well in view with NOAA's vision and mission that establish a comprehensive understanding of the role of the oceans and coasts to meet our Nation's economic, social, and environmental needs. It is aligned with the new priorities for the 21st century presented in the NOAA's strategic plan and in regards of coastal and marine resources through an ecosystem approach to management. The research activities are helping to develop better and most cost-effective tools to monitor coastal processes.

- **Relevance to NOAA Line Office (i.e., National Weather Service, National Ocean Service) strategic plan:** This project provides critical support for NOAA's missions of the National Ocean Service by using and validating environmental satellite data. Especially, it is creating an important database of bio-optical properties from coastal waters affected by rivers discharge. These field data are crucial to develop improved algorithms for the estimation of water quality parameters in coastal waters.

- **Supervising PI or Co-Is:** Fernando Gilbes Santaella

- **Publications (during performance period):**

  -Peer Reviewed Article:
  - ❖ Vilmaliz Rodriguez is currently working in a paper of her second thesis chapter. It will be submitted to a scientific journal very soon.

  -Book:
  - ❖ Work has continued for the peer-review book about the oceanography and remote sensing of Mayaguez Bay, including all the work sponsored by NOAA CREST. This book will be published in collaboration with the Center for Hemispherical Cooperation (CoHemis) of UPRM.

- **Dollar amount of funds leveraged with CREST funds (during performance period):**

Project Title	Sponsoring Agency	PI/Co-PI/ Recipient/Group	Dollars	Start Date	End Date
Developing a protocol to use remote sensing as a cost effective tool to monitor contamination of mangrove wetlands	University of Puerto Rico Sea Grant College	PI: Johannes Schelekens Co-PI: Fernando Gilbes	$30,000 (No cost extension)	June 2006	December 2010

- **Ongoing, New or Revised?:** Ongoing
- **Staff:** None
- **Students PhD:** None
- **Students MS:** Natlee Hernandez, UPRM-Dep. Of Geology
- **Students Undergraduate:** None
- **NOAA Collaborators:** A site-specific algorithm has been developed and tested to estimate Total Suspended Sediments (TSS) in Mayaguez Bay. This algorithm is being incorporated in NOAA-NESDIS system as a "testing product" of TSS for Puerto Rico in collaboration with Joaquin Trinanes, Acting NOAA Coast Watch Operations Manager for the Caribbean Regional Node.
- **Other Collaborators:** Roy Armstrong (UPRM-Department of Marine Sciences).
- **Operational Impact:** The on-going project aims to develop the appropriate techniques to use ocean color sensors to monitor the conditions of coastal environments. Estimates of Chlorophyll and Suspended Sediments from space can be used as proxy for the quality of coastal waters. Continuous monitoring of such parameters with satellite sensors will help to better understand and manage our coastal environments.
- **Status of the project with respect to the goals/objectives and benchmarks previously identified:** Vilmaliz Rodriguez successfully defended her thesis on December 8, 2009. This work was fully funded by NOAA-CREST and covered several tasks of this thrust. A site-specific algorithm for the estimation of Total Suspended Sediments in Puerto Rico coastal waters was developed and its implementation as "testing product of the NOAA CoastWatch program is underway. Remote sensing reflectance measurements obtained with the GER-1500 spectroradiometer were used to estimate this parameter and compared with MODIS data. Her work also helped to create the on-line GIS-database of the GERS Lab (GERSVIEW) and to evaluate a model for land-sea interface studies. A new effort by Natlee Hernandez is now in progress to better understand the effect of suspended sediments on the remote sensing reflectance. Good progress has been obtained in all proposed tasks.

Tasks (as per the Milestone Chart)

Task: Compare to satellite water leaving products and atmosphere retrievals

This task was mostly completed in Mayaguez Bay by Vilmaliz Rodriguez during the last semester. In this reported period we developed the sampling protocols to measure total suspended sediments (TSS), backscattering (bb and bbp), and Remote Sensing Reflectance (Rrs) in the mouth of the rivers. This work will start this semester by Natlee Hernández. As part of this task we also started the processing of the optical data collected in La Parguera.

Task: Intercomparison of below/above water signals with aircraft and satellite data as available.

Development and validation of an algorithm to estimate total suspended sediment (TSS) was performed based on *in situ* remote sensing reflectance (Rrs) and MODIS/Terra band 1 data. Additional data and pre-processing parameters should be evaluated in order to improve validation results and produce TSS operational products for tropical coastal waters. The processing in Mayaguez Bay has shown that improvements in the atmospheric correction are necessary. Natlee Hernández is now conducting several processing procedures in order to determine the best algorithms for the removal of the atmosphere in these coastal waters. This effort will allow obtaining better estimates of TSS.

Task: Analysis of optical field measurement together with Chl, TSS concentrations
A new effort has started in order to understand how the sediments of the Añasco, Yagüez and Guanajibo rivers affect the optical signal of Mayagüez Bay. This work is based on recent findings by Vilmaliz Rodriguez and is performed by Natlee Hernandez. Remotely sensed and *in-situ* measurements are going to be used. Determination Physical and geological characteristics of the suspended sediments will help us to understand the behavior of the spectral responses. The XRD and the Sedigraph 5100 instruments will be used to determine the mineral composition and the grain sizes. The MERIS ocean color sensor from the ESA (European Spatial Agency) data will be compared to in-situ measurements. Finally, all the data will be associated to the season in which was collected and correlated to the physical characteristics of the particles. During this semester field work and laboratory analyses will begin by Natlee.

Task: Development of GIS database for land sea interactions in Mayaguez Bay
Quality control of all data collected in Mayaguez Bay was continued during the reported period. In addition, new analyses of the collected optical data in La Parguera were started. These data set was not included during the first round of processing because the nature of processing and quality control is more complicated and requires particular attention. Transfer of knowledge between Vilmaliz Rodriguez and Natlee Hernandez continued in order to further develop the GERSVIEW database.

Task: Development of GIS model for land-sea interactions in Mayaguez Bay.
This task was completed by Vilmaliz Rodriguez last semester and it is described in her M.S. thesis. She used the Revised Universal Soil Loss Equation (RUSLE) in Mayagüez Bay watershed in a GIS based model.
Further details can be found in http://gers.uprm.edu/pdfs/thesis_vilmaliz.pdf.

Future Tasks (From the Milestones)
Efforts for developing site-specific algorithms for suspended sediments will continue. This will include a better understanding of the physical and geological characteristics of sediments. Optical data from La Parguera are being organized and will be added to the GIS databases. Very soon they will be exported to GERSVIEW on-line database (http://gersview.uprm.edu). This activity will allow people to access and manipulate the data via internet for better understanding of land-sea interactions in coastal waters of Puerto Rico. Natlee Hernández will continue working with this important aspect of the project. Another publication by Vilmaliz Rodriguez will be submitted to a peer-review journal very soon. The PI and other students will continue working with the chapters of the Mayaguez Bay book.