

Using MODIS 250 m Imagery to Estimate Total Suspended Sediment in a Tropical Open Bay

Vilmaliz Rodríguez-Guzmán and Fernando Gilbes-Santaella

Abstract—Monitoring and better understanding of sediment flux and processes in coastal environments are important to maintain water quality and geomorphologic balance. This study describes the development and validation of an algorithm to estimate total suspended sediment (TSS) based on remote sensing reflectance (R_{rs}) and MODIS/Terra band 1 data. Two image processing methods, based on two image analysis packages predefined routines, were evaluated and compared in order to determine the most suitable method for this study. Analyses of *in situ* data showed a significant relationship between TSS and R_{rs} at 645 nm ($R^2=0.73$) 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 will be evaluated in order to improve validation results and produce TSS operational products for tropical coastal waters.

Keywords— Total Suspended Sediments (TSS), Remote Sensing Reflectance (R_{rs}), MODIS, coastal waters, Mayagüez Bay.

I. INTRODUCTION

Mayagüez Bay is an open bay located at the west part of Puerto Rico between latitude N 18° 09' to 18° 18' and longitude W 67° 09' to 67° 15' (Fig. 1). This area provides exceptional resources to study inshore processes and coastal dynamics that can be used as baseline for the development of biogeo-optical algorithms in tropical coastal waters. As many other coastal environments this bay is highly affected by inland processes including sediment and nutrients fluxes and anthropogenic derived discharges. The concentration of total suspended sediment (TSS) is considered one of the most important water quality parameters [1] and can produce non-

point source pollution. For instance, high concentrations of suspended sediment reduce light penetration through the water column affecting primary production of an ecosystem. Therefore distribution and abundance of TSS is of great importance when evaluating the condition of a coastal system. However, it is a great challenge to develop methods that assist in the monitoring and assessment of these processes especially at broad scales [2]. This limitation is reduced by incorporating remote sensing techniques where desire information can be retrieved from spectral data collected using a remote platforms. Satellite technologies are widely used to quantify and monitor water quality parameters in coastal waters. Empirical algorithms are used to derive satellite estimations of water constituents (e.g. Chl-a, CDOM and TSS) which reduce field work and help covering large areas. The development of these algorithms normally involves the establishment of empirical relationships between the satellite derived data and *in situ* measurements. This is based on the principle that variations in spectral response can be associated to specific water constituents. Several studies have used satellite derived data to estimate TSS to monitor water turbidity [3], sediment resuspension [4] and other novel applications such as the estimations of deposition rates [5].

Numerous sensors have been developed for different ocean color applications, including water turbidity assessments, sensors such as AVHRR, SeaWiFS, MODIS, IKONOS, Landsat TM and ETM+. Variations in temporal and spectral resolutions, data availability, calibration issues and temporal coverage are some of the most important factors determining the selection of the best instrument for a particular study [6]. MODIS provides a good temporal resolution (1 day) for monitoring purposes; however, the spectral sensitivity of this sensor decreases as the spatial resolution increases. It is well known that in Case 2 waters the leaving signal is highly dependant of TSS concentration specially in wavelengths longer than 500 nm [7-8-9]. Therefore MODIS band 1 (250 m), which covers the range between 620 to 670 nm, contains potential data to estimate TSS. Although this band was originally created for land applications, previous studies have validated it used for water quality studies in coastal and estuarine waters [10-2-11-12]. The application of previously formulated ocean color algorithms for the estimation of water constituents is generally limited by site-specific factors [13], and presently there is no uniform remote sensing based model to estimate TSS [1]. Limiting factors in Mayagüez Bay are primarily the combination of working in a relatively small area (~95 Km²), the presence of optically complex waters [14]

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and a relatively small range of TSS values. On the other hand, one of the most determinant aspects when using satellite images to retrieve water quality parameters is the atmospheric correction. In this study we have compared and evaluated the results of two atmospheric correction methods available in two different image analysis packages: ENVI (Dark Subtract) and SeaDAS (l2gen command). The present study is focused in the development, evaluation and validation of site-specific algorithms to estimate TSS based on MODIS reflectance band 1.

II. METHODOLOGY

This study aimed to establish empirical relationship between *in situ* measurements of TSS concentration, MODIS band 1 reflectance and *in situ* remote sensing reflectance (R_{rs}) as measured with a field spectroradiometer. This approach will show the potential of MODIS sensor for TSS estimations and determine the best method to develop an algorithm for this purpose.

A. *In situ* measurements

All *in situ* data were collected during research cruises between January 2004 and October 2006 in a set of stations distributed along the bay (Fig. 1). Table 1 shows the dates included in this analysis which correspond to research cruises where MODIS data were available. R_{rs} was computed with measurements collected with the GER-1500 field spectroradiometer and using the following equation:

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

Where f is the Fresnell coefficient equal to 0.028 at 45° [15]. The curves were corrected for sky-light reflection subtracting the minimum measured value between 900-920 nm, and in a few cases using lower spectral regions (730-900 nm). It was not possible to select a specific wavelength because sampled stations include both clear and turbid waters and these conditions affect the determination of the most appropriate wavelength for this correction [16]. Water samples were collected at approximately at the depth of 1 meter deep in six stations to measure TSS, which corresponded to all the material larger than 0.7 μm . Concentration of TSS (in mg/l) was determined using the standard weight difference method [17].

B. MODIS Data

Two different processing methods were used to generate functional MODIS products. One was based on pre-processing routines available in ENVI software and the second used SeaDAS commands (Fig. 2). Images collected by the Moderate Resolution Imaging Spectroradiometer (MODIS) during the same sampling dates were downloaded through two NASA Internet servers: LAADS Web and OceanColor Web. For the first method the product selected at LAADS Web was MOD02QKM, which includes reflectance and radiance values

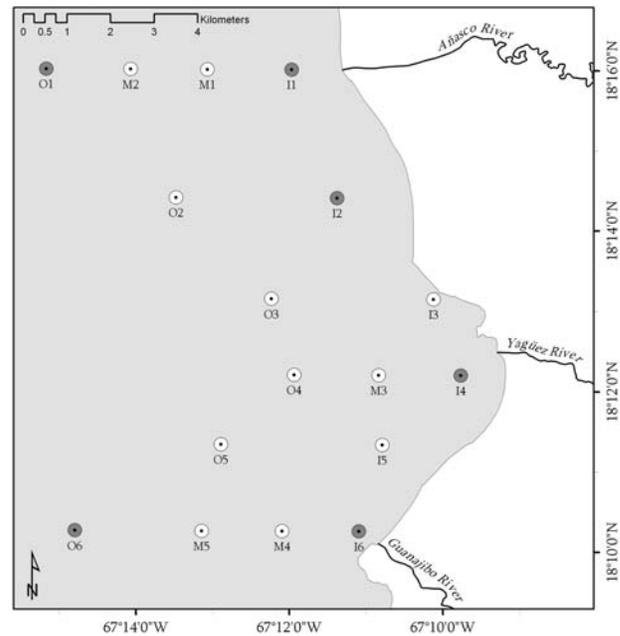


Figure 1. Study area (Mayagüez Bay at western Puerto Rico) showing the location of sampling stations. Stations colored in white indicate specific sites that were sampled only during special missions, while six stations in gray are permanent stations.

of MODIS/Terra band 1 and 2. All these images were processed using ENVI (v. 3.4) processing routines: MODIS Georeference and Dark Subtract. The spatial reference system was defined as UTM NAD83 for Puerto Rico region. The dark subtract atmospheric correction consists in the selection of the darkest value in band 2 and subtract it to all band 1 data. This value was manually identified in each image and then defined in the “User Value” option of this routine. For the second method, L0 data were downloaded at the OceanColor Web browser. This data were processed using SeaDAS MODIS commands from level 0 to level 2. The program L2gen uses as input L1b data and generates level 2 products by applying atmospheric corrections and bio-optical algorithms [18]. Conditions in these waters suggested that the best algorithm for atmospheric correction available in SeaDAS is the one that performs multiscattering switching between Near Infrared (NIR) and Short Wave Infrared (SWI) bands (J. Trinanés, personal communication). However, additional algorithm corrections, available within L2gen command, were evaluated in order to improve the results. After generating L2 products, the data were projected as UTM NAD83 using SeaDAS Map Projection command.

C. Algorithm Development and Validation

A The algorithm consisted in the combination of two equations, one defining the relationship between field R_{rs} and TSS, and other establishing the relationship between field R_{rs} at 645 nm and MODIS band 1. Data collected during thirteen sampled days were used to develop the first equation, while

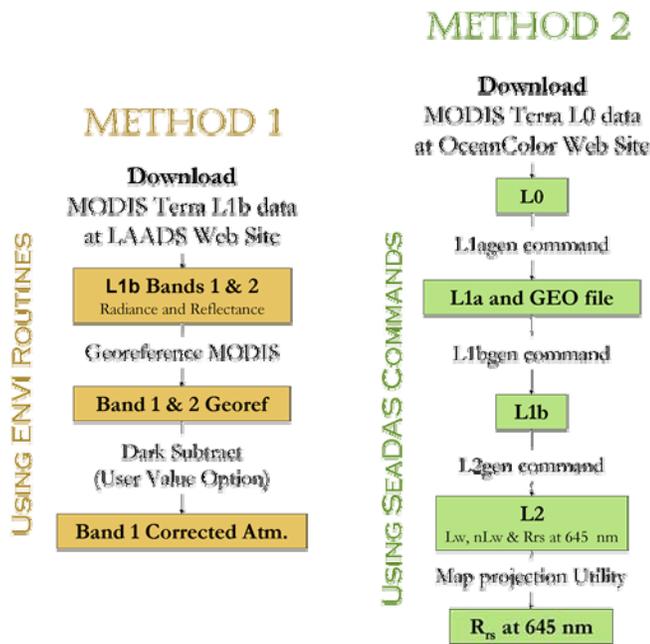


Figure 2. Schematic illustration of two methods used to process MODIS data. Method 1 is based in ENVI image processing software and Method 2 uses SeaDAS specialized commands.

this number was limited to five for the second equation. This difference was mainly due to the lack of good quality images suitable for analyses, which affected the development of the second equation. MODIS reflectance values were extracted from pixels corresponding to stations monitored for R_{rs} . Developed equations were applied to two images (February 12, 2004 & March 8, 2008), which were not incorporated in the previous analysis and *in situ* data were available in order to validate developed algorithms. Application of the equations was possible using ENVI band math tool, which contains easy to use options to ingrate image bands in mathematical equations.

Proficiency of the algorithms was evaluated by comparing estimated and observed values in a root mean square error (RMSE) analysis. Additionally, obtained TSS products were visually analyzed in order to evaluate and identify spatial patterns associated to this type of environment. Finally, resultant values corresponding to Mayagüez Bay area were extracted for statistical analyses. The Mayagüez Bay area was digitalized by visual interpretation using orthorectified aerial photograph (2006) and saved as a polygon shapefile (ArcGIS 9.3, ESRI). This shapefile was then imported to ENVI using its vector files menu options and converted to a Region of Interest (ROI), from which was very simple to extract the information of all pixels in the area of interest.

A. MODIS Products

The first method resulted on seven reflectance products at 645 nm (band 1), one for each research cruise dates. Three different products for each date were generated using the second method: Remote sensing reflectance (R_{rs}), Leaving Water Radiance (L_w) and Normalized Leaving Radiance (nL_w). For purposes of this study the target product was R_{rs} at 645 nm, however resultant values in this and the rest of generated products were mostly negative and with flagged values. This suggested that the standard method for processing MODIS data in SeaDAS is not suitable for application in this type of waters characterized by high concentrations of TSS and other water constituents in comparison to oceanic waters. Low and negative values indicated that the applied atmospheric correction it removed also part of the water leaving signal while flag values in the coast suggest that the algorithm is identifying as errors highly contrasting reflectance values. Variations between Case 1 and Case 2 water limits generation of standard satellite products [19]. These processing algorithms are mainly developed for oceanic waters applications, therefore they are not able to recognize as good values, patterns that are typical in coastal waters. One potential option to minimize the number of flag values is to adjust the different parameters available in the flags menu option within the L2gen command, but this approach is not included in this analysis. Table 2 shows reflectance values and *in situ* R_{rs} 645 nm values obtained in locations of sampling stations during October 19, 2005. The satellite derived reflectance is considerably lower than *in situ* R_{rs} suggesting a significant effect of atmospheric scattering in the signal.

Stat. ID	Latitude (N)	Longitude (W)	Method 1 Reflectance at 645 nm	<i>in situ</i> R_{rs} at 645 nm
I1	18° 16.00'	67° 12.00'	0.047406	0.0130
O1	18° 16.00'	67° 15.20'	0.018792	0.00118
I2	18° 14.40'	67° 11.40'	0.027528	0.0041
O2	18° 14.40'	67° 11.40'	0.019948	0.0007
O4	18° 12.20'	67° 12.95'	0.016265	0.0005
I6	18° 10.25'	67° 11.10'	0.027037	0.0081
O6	18° 10.25'	67° 14.80'	0.014844	0.0005

Table 2. Pixel values obtained in permanent sampling stations using two different image processing methods and *in situ* R_{rs} at 645 nm.

B. Total Suspended Sediment Algorithm

A significant relationship ($R^2=0.73$; $n=72$) was defined between TSS (mg/l) and *in situ* R_{rs} at 645 (Fig. 3a). This result suggests that this region of the spectrum is suitable for TSS estimation using remotely sensed data in these waters. However, a large unknown variability was detected in this equation that could be reduced by the incorporation of more

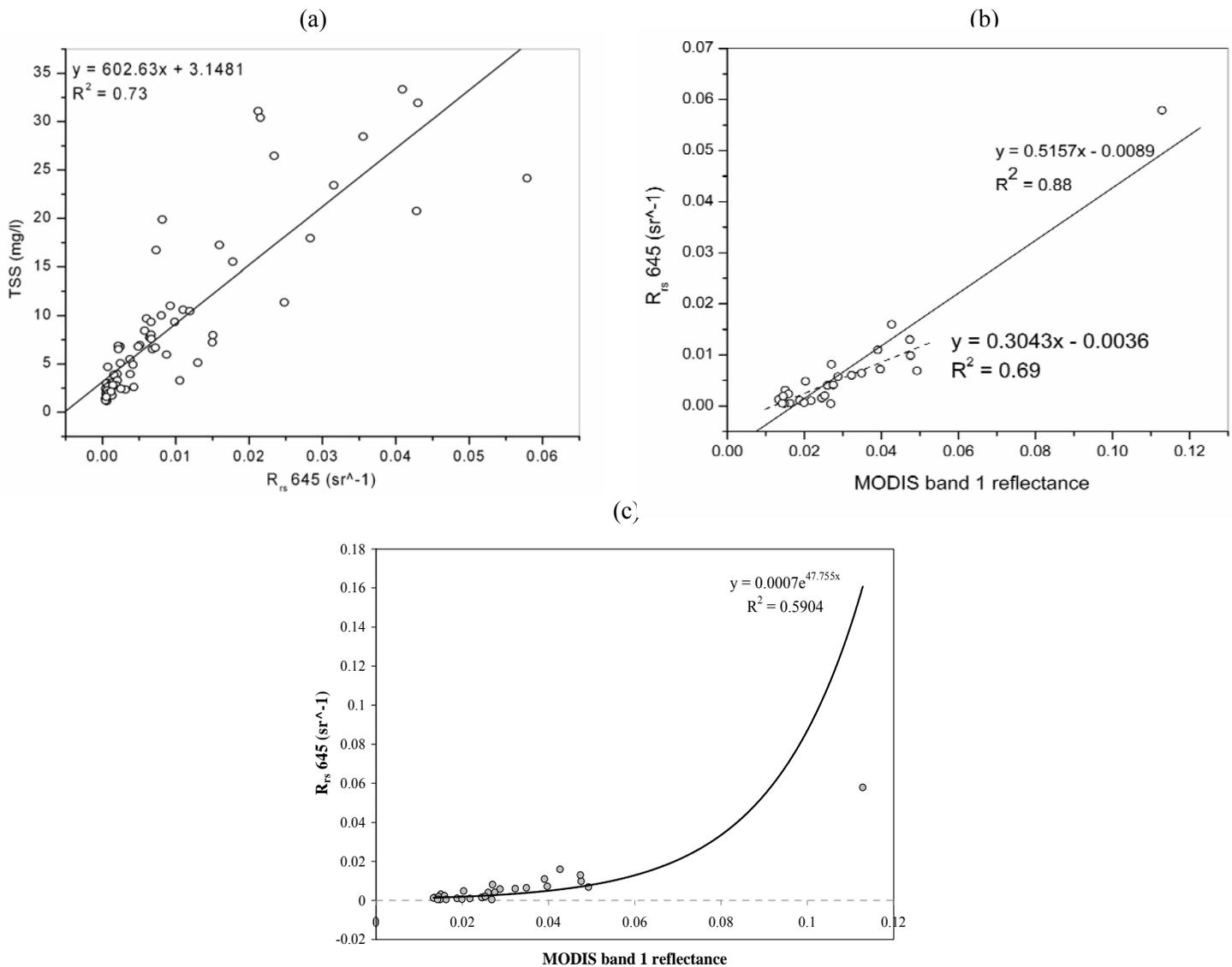


Figure 3. Data used to develop a TSS algorithm for Mayaguez Bay; (a) Relationship between *in situ* R_{rs} at 645 nm and TSS, (b) Two linear equations and (c) one exponential equations defining the relationship between *in situ* R_{rs} at 645 nm and MODIS band 1 reflectance.

observations. Two linear equations were defined to establish the relation between TSS (mg/l) and R_{rs} at 645 nm (Fig. 3b) because of the presence of an extreme value. The higher square correlation coefficient ($R^2=0.88$; $n=30$; $P<0.0001$) was observed when incorporating such extreme value. The strong relationship between these two parameters indicates a high correspondence between MODIS reflectance and *in situ* R_{rs} . A decrease in both, slope and square correlation coefficient ($R^2=0.69$; $n=29$; $p<0.0001$) is observed when the extreme value is excluded. This value could be representative of rare, but real conditions; therefore, more sampling associated to high river discharge is necessary to validate this relationship. It was observed that when working with low reflectance values resultant estimations tended to be negative or extremely low, therefore an exponential equation was incorporated in this analysis in order to minimize this effect (Fig. 3c). The square correlation coefficient of this equation was lower ($R^2=0.59$) than when using linear equations. Based

on these analyses the following algorithms were implemented and tested:

$$TSS = 602.63 * (0.5157 * (\text{MODIS band 1}) - 0.0089) + 3.1481 \quad (1)$$

$$TSS = 602.63 * (0.3043 * (\text{MODIS band 1}) - 0.0036) + 3.1481 \quad (2)$$

$$TSS = 602.63 * (0.0007e^{47.755 * \text{MODISband1}} + 3.1481 \quad (3)$$

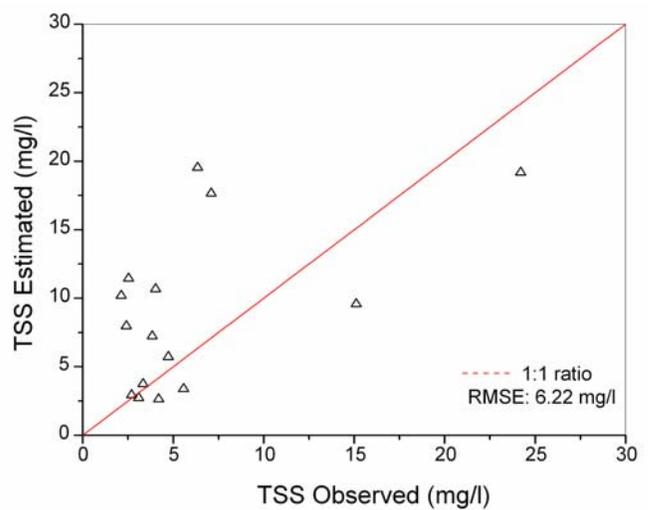
C. Total Suspended Sediment Algorithm Validation

For validation purposes, equations (1), (2) and (3) were applied to two images corresponding to cruises dates (Feb 12, 2004 and March 8, 2006) not included in the development of the equations. The first two algorithms resulted in RMSE higher than 5 mg/l (Fig. 4a-b) while the lower RMSE (4.8 mg/l) was encountered when using equation 3 (Fig. 4c).

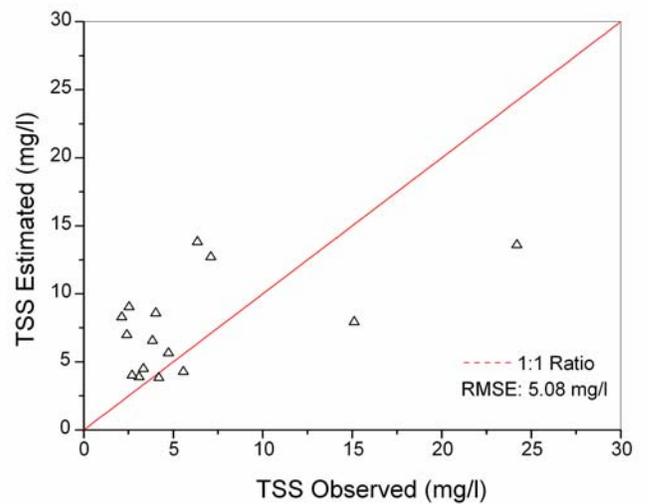
Comparison between these validation results indicated that equation 3 was able to better estimate TSS in lower concentrations, but during higher concentrations it tended to underestimate this parameter. Although equation 1 showed a higher RMSE, estimated values followed better the tendency of observed values. The limitations of these algorithms can be attributed to various factors: (i) limited data representative of high TSS concentrations, (ii) MODIS band 1 is not capable of detecting TSS signal under low concentrations conditions, (iii) the atmospheric correction method is not appropriate, and (iv) the presence of sea-bottom effect in the signal. Another problem that could be affecting the results is the mixing pixel phenomenon; which is a common and highly influence problem when trying to derive information from satellite imagery [20]. In the case of TSS estimations, the mixing pixel occurs when variations in TSS concentrations or land and water areas are combined within the 250 m cover area of a pixel. Occurrence of this phenomenon can be reduced by using images with higher spatial resolution, but this alternative is limited by current ocean color sensors.

D. Total Suspended Sediment Products

Estimations of TSS were generated using the three developed algorithms in order to spatially analyze results and compare efficiency of the equations. Figure 5 shows spatial variations associated to TSS concentration in Puerto Rico surroundings areas and Mayagüez Bay for the dates used in the validation analysis. The spatial variability observed in these products appeared to respond by inshore processes showing higher concentrations in areas closer to the shoreline which are typical characteristics of coastal environments. In the case of Mayagüez Bay the majority of high values are concentrated in the northern part of the bay where the Añasco River plume is located. Comparison between all three different algorithms does not indicate any significant difference between them; the main difference resides in algorithm 3 which range of values is considerably higher than the algorithm 1 and 2. Therefore, application of algorithm 3 resulted on sharper spatial variations when comparing values in inshore and offshore areas.



(b)



(c)

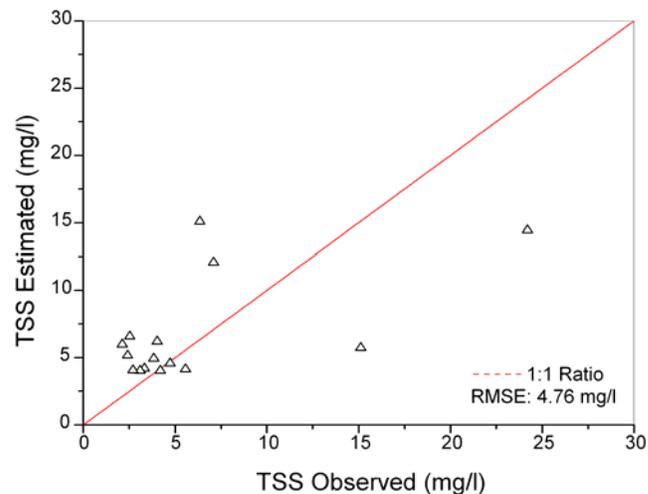
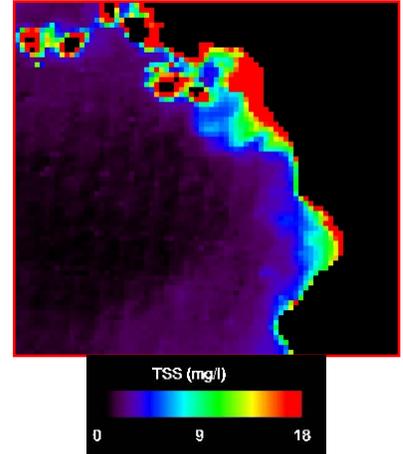
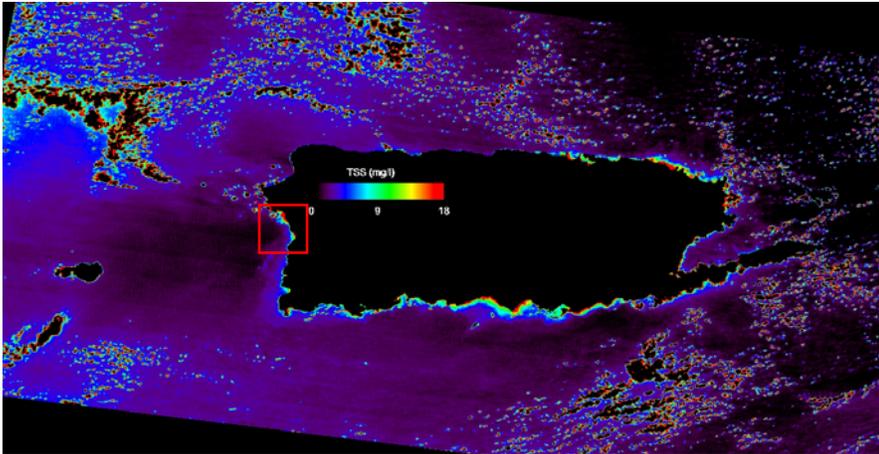


Figure 4. Validation results when applying (a) equation 1, (b) equation 2 and (c) equation 3.

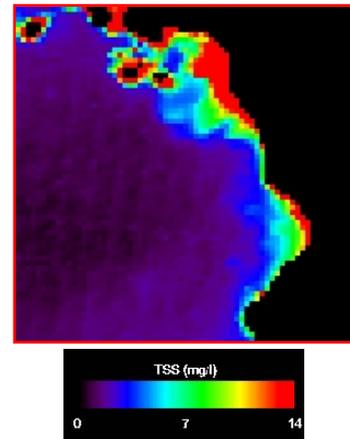
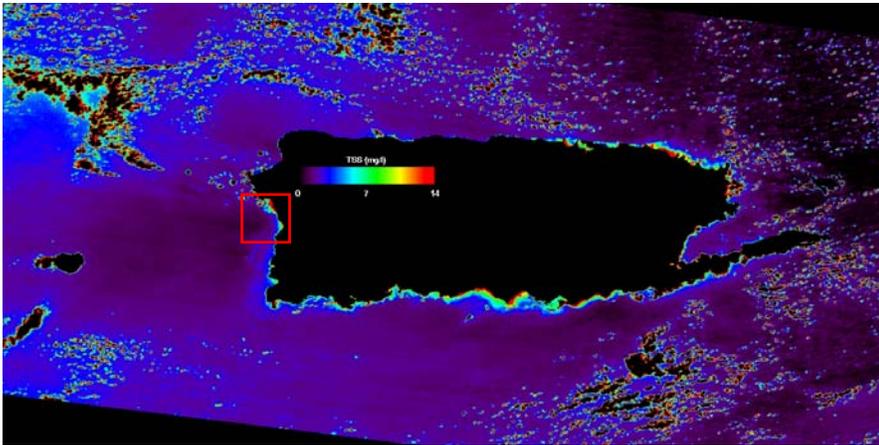
(a)

(a) February 12, 2004

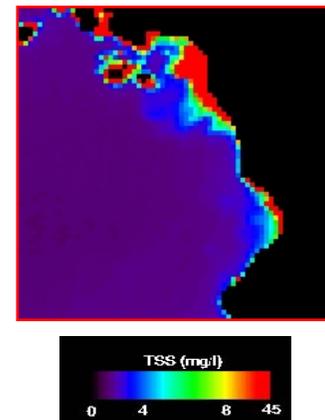
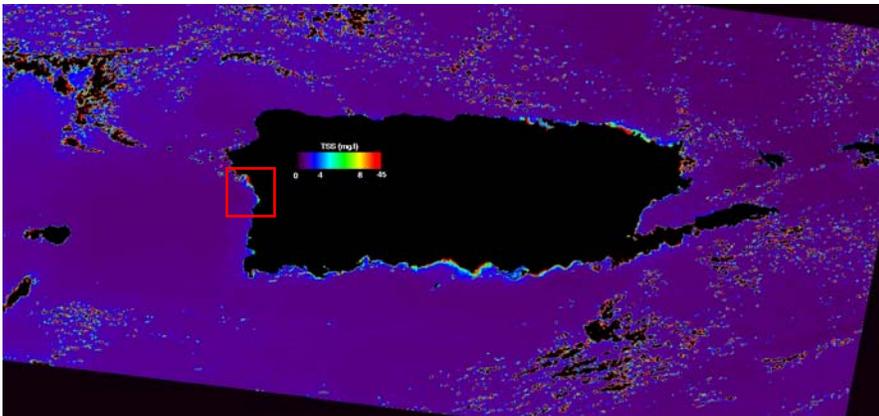
Algorithm 1



Algorithm 2

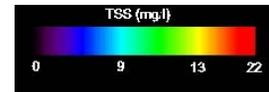
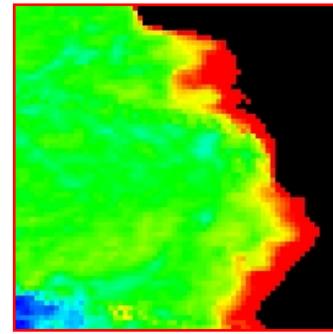
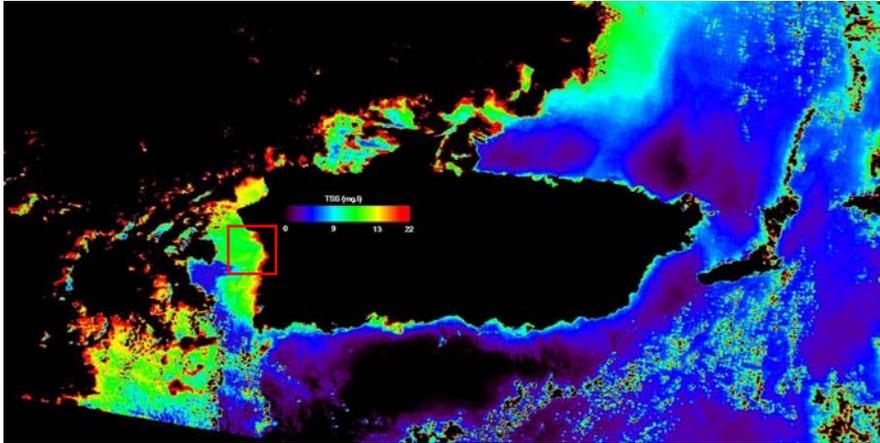


Algorithm 3

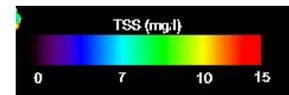
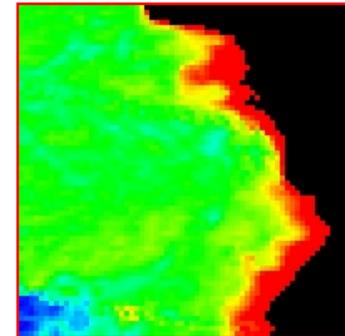
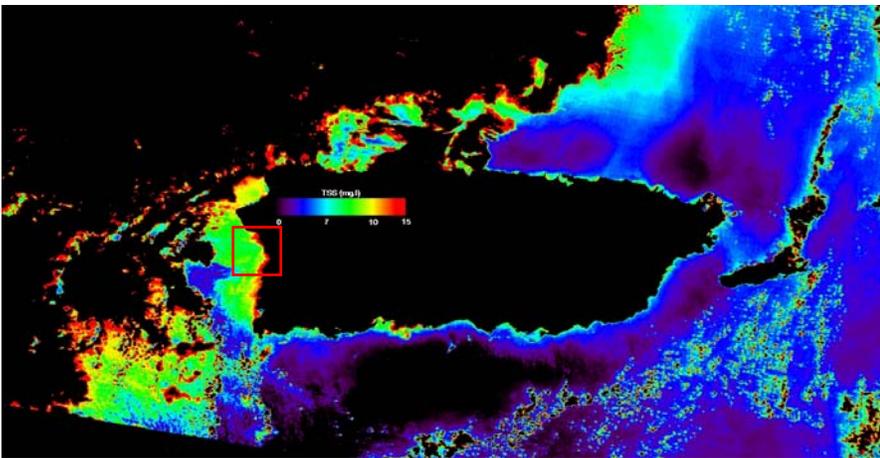


b) March 8, 2006

Algorithm 1



Algorithm 2



Algorithm 3

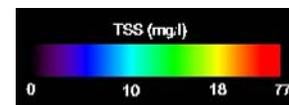
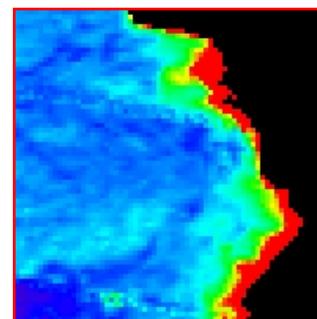
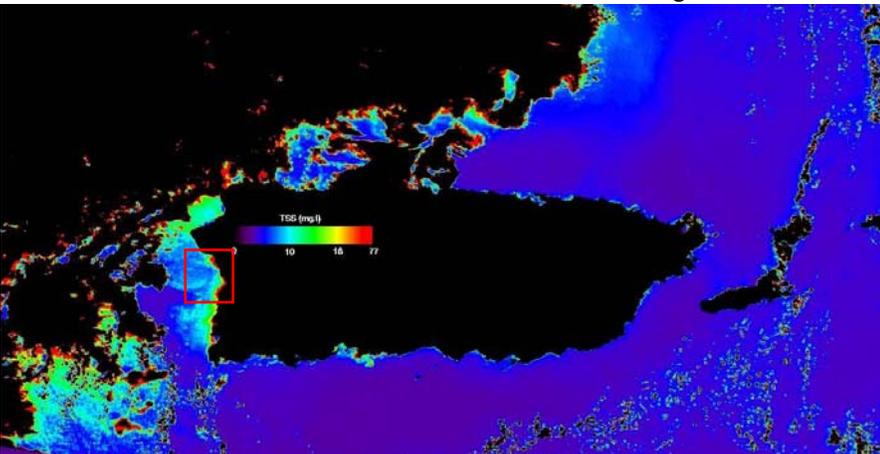


Figure 5. TSS products generated using three developed algorithms based on MODIS band 1 data for two dates (a) February 12, 2004 and (b) March 8, 2006. Mayagüez Bay indicated with the red box and a close up is shown on the right side. Note the differences in scale values of the color palettes.

TSS estimated values corresponding to Mayagüez Bay area were extracted and analyzed using basic statistics. Figure 6 illustrates the distribution of TSS values using both field data (Study Period: January 2004-October 2006) and generated TSS products for February 12, 2004. Direct comparison between these data sets has been made considering the following statements: (i) sampling stations are distributed along the bay covering inshore and offshore areas (ii) TSS measurements used in this analysis includes only surface samples (iii) selected date for this analysis (February 12, 2004) presents commonly occurrence conditions in this bay. Mean values for all products (4.6,

5.0, 5.6 mg/l) were highly comparable to *in situ* mean value (5.9 mg/l) and all showed positive skewed distributions (Fig. 6). Minimum values of algorithms 2 and 3 (> 3.0 mg/l) indicates that these results can be overestimated considering that this analysis includes areas where TSS concentrations are normally lower than 2.0 mg/l (e.g. offshore in the southern part of the bay). Algorithm 1 presented the higher similarity with the distribution of *in situ* TSS measurements (Fig. 6b). However, in order to determine which estimations better followed real conditions, spatial analysis of *in situ* measurement of that particular day should be incorporated.

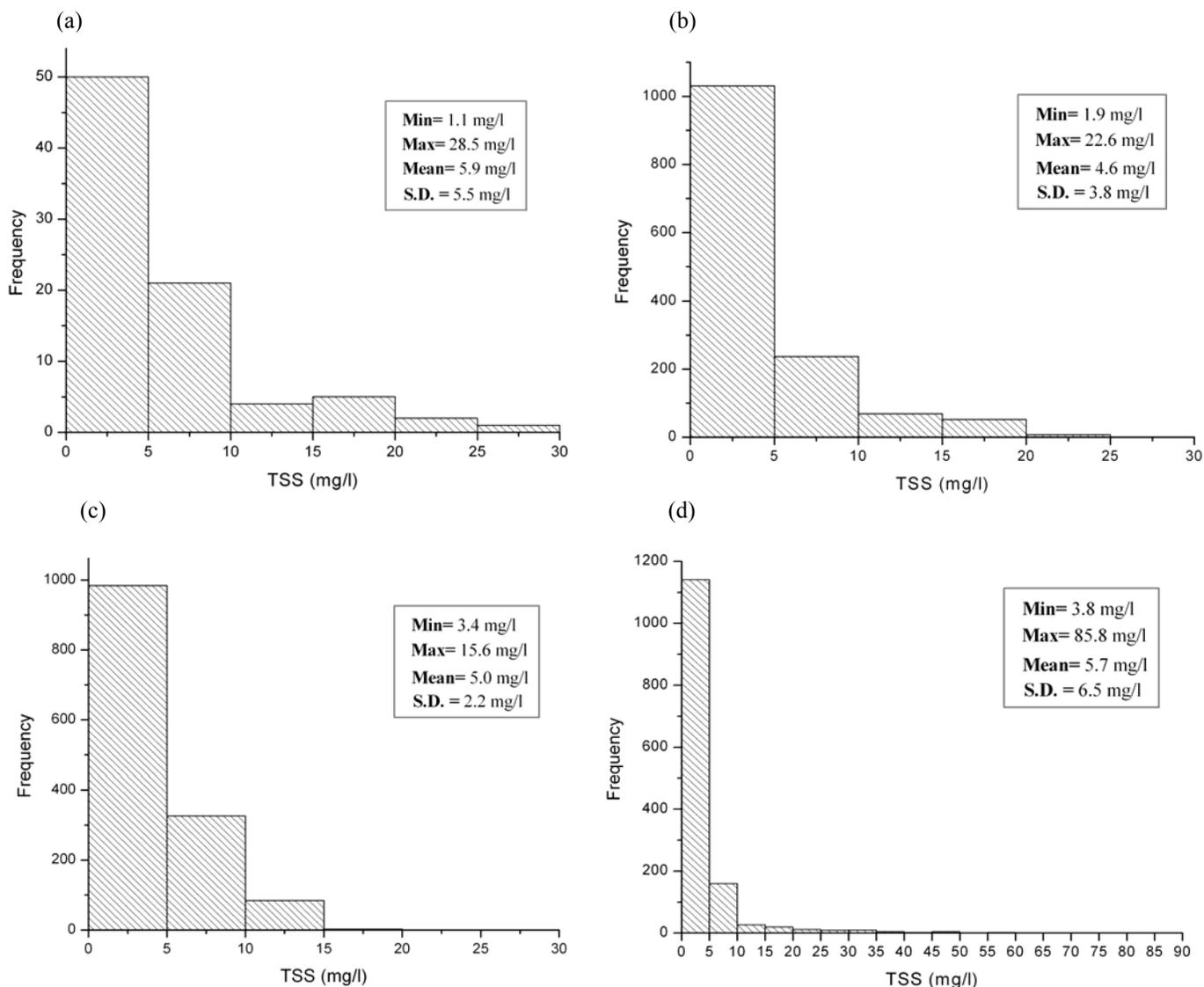


Figure 6. Descriptive statistics and histograms illustrating TSS values distribution for (a) *in situ* measurements collected within the study period (January 2004-October 2006) and TSS products generated using (b) algorithm 1, (c) algorithm 2 and (d) algorithm 3.

IV. CONCLUSION

Geometric and radiometric corrections utilized during image pre-processing routines are crucial for this type of analysis. Atmospheric correction included in L2gen command (SeaDAS) is not suitable for application in Mayagüez Bay waters. This same result is expected to find in other tropical bays. Fairly good empirical relationships were defined between *in situ* R_{rs} , TSS and MODIS band 1 data using linear and exponential equations. Application of developed equations resulted on TSS products able to detect spatial variations associated to typical patterns of coastal environments. Algorithm 3 showed the higher correspondence between observed and estimated values (RMSE 4.76 mg/l). However, all three algorithms resulted in reasonable TSS pixel values when compared with data from *in situ* measurements therefore at this point none of the algorithms is excluded for future application. Using an exponential equation resulted in a more suitable approach for this study purpose, since the algorithm including this equation was more effective estimating low values which are the dominant conditions in the studied bay. Validation results can be improved by addressing limiting factors such as lacking of data corresponding to high concentrations, and contamination by the remaining atmospheric effect in the derived reflectance of the sensor. The results obtained in this study provide a baseline to develop TSS operational products for tropical coastal waters by developing preliminary products and identifying potential errors and limiting factors in the process.

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