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Article

Using the Surface Reflectance MODIS Terra Product to Estimate Turbidity in Tampa Bay, Florida

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Abstract: Turbidity is a commonly-used index of the factors that determine light penetration in the water column. Consistent estimation of turbidity is crucial to design environmental and restoration management plans, to predict fate of possible pollutants, and to estimate sedimentary fluxes into the ocean. Traditional methods monitoring fixed geographical locations at fixed intervals may not be representative of the mean water turbidity in estuaries between intervals, and can be expensive and time consuming. Although remote sensing offers a good solution to this limitation, it is still not widely used due in part to required complex processing of imagery. There are satellite-derived products, including the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra surface reflectance daily product (MOD09GQ) Band 1 (620–670 nm) which are now routinely available at 250 m spatial resolution and corrected for atmospheric effect. This study shows this product to be useful to estimate turbidity in Tampa Bay, Florida, after rainfall events

(R^2 = 0.76, n = 34). Within Tampa Bay, Hillsborough Bay (HB) and Old Tampa Bay (OTB) presented higher turbidity compared to Middle Tampa Bay (MTB) and Lower Tampa Bay (LTB).

Keywords: water quality; light attenuation; turbidity; estuarine remote sensing; rainfall; color

1. Introduction

With increasing human populations in coastal urban areas, there is a growing need to monitor water quality in coastal aquatic ecosystems adjacent to urban watersheds. Sediment or high phytoplankton concentrations can block sunlight from reaching benthic algae and sea grass, negatively affecting biological and physical processes. Turbidity is an index of light attenuation and water quality commonly used in estuarine and coastal areas. It is also an important index of impacts of coastal erosion or agricultural and urban nutrient discharges. Therefore turbidity can be used to estimate the distribution, discharge and fluxes of suspended sediments and possibly pollutants [1,2]. Turbidity may be estimated by remote sensing techniques in coastal, turbid waters [2,3], in contrast to chlorophyll-a (a direct estimator of phytoplankton abundance), which is not reliably estimated in Coastal waters [4] due to the higher presence of Colored Dissolved Organic Matter (CDOM) and other factors including bottom reflectance [5,6].

The application of remotely sensed data to the monitoring of coastal water quality has a great advantage over conventional *in situ* methods at fixed stations. Satellite sensors can cover wider areas in a synoptic manner [7] . They also have important disadvantages. They may not provide the spatial and temporal resolution required to cover some particular processes [8], accessibility of the data, technical procedures needed for sensor calibration and radiometric correction, and the cost and complexity of implementing algorithm and data processing systems have limited use in the past. A study conducted in Mayaguez Bay, Puerto Rico, used Moderate Resolution Imaging Spectroradiometer (MODIS) Terra 250 m, band 1 (645 nm), to estimate suspended sediment after correcting for atmospheric effects [9]. A previous study of Tampa Bay also demonstrated that MODIS Aqua 250 m data, band 1 (645 nm), can be used to monitor turbidity with a simple algorithm after rigorous atmospheric correction [8]. NASA has now made available the 250 m spatial resolution MODIS Terra "surface reflectance" product (MOD09GQ), which is atmospherically corrected. A study conducted in Gironde Estuary, France, used this product and its equivalent from the Aqua satellite (MYD09GQ) in a ratio of bands 2 (around 850 nm) to 1 (around 650 nm) to quantify concentrations of suspended particular matter in highly turbid waters [10]. In the three cases, concentration of suspended sediments/turbidity was retrieved empirically. Issues such as bottom reflectance contamination and interference of high concentration of CDOM still warrant the examination of more extensive time series of these MODIS observations of Tampa Bay.

This study applies an empirical method to establish a relationship between *in situ* measurements of turbidity in Tampa Bay and atmospherically-corrected reflectance in band 1 (620–670 nm) from the MODIS Terra sensor (reflectance product MOD09GQ; R_{rs}) testing the feasibility of using this standard

NASA product. This relationship is used to develop an algorithm to estimate water turbidity from satellite imagery taking into account depth and number of days since the previous rain event. Optical absorbance at 350 nm, measured *in situ* as part of routine water quality observations, was also considered. Caution should be taken to apply this empirical algorithm under different geographical and limnological conditions due to the strong dependence of the turbidity and reflectance on physical, biological, and mineral composition of particles and dissolved materials [3,11,12]. Although these characteristics are particular to each water body and watershed, the approach followed here can be applied to other estuaries and bays.

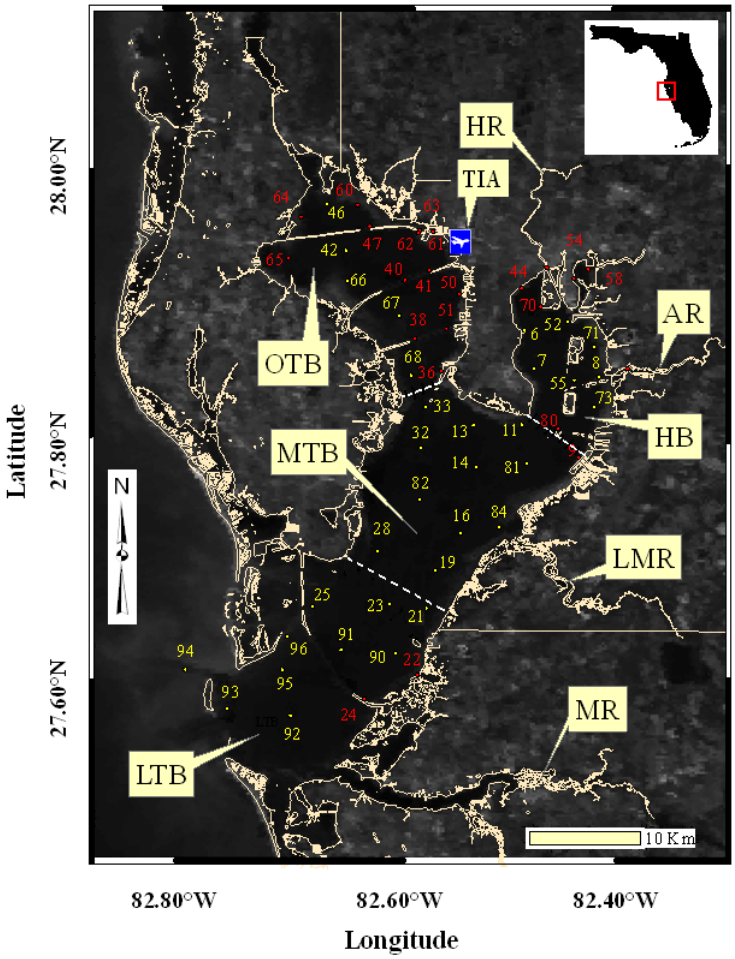
2. Methods

2.1. Study Area

Tampa Bay is located on the west-central coast of the Florida Peninsula between 27.5–28.08°N and 82.36–82.75°W (Figure 1). Air temperatures in the area range between about 4 °C in the winter and 39 °C in the summer. About 60 percent of the annual precipitation occurs during summer (approx. 76 cm) [13]. The total precipitation at the Tampa International Airport (TIA) (27.96°N, 82.54°W) during the 2000–2007 period was 965 cm. Based on data from the Environmental Protection Commission of Hillsborough County (EPCHC) at 56 fixed stations in Tampa Bay, the average values of Secchi disk depth, turbidity, concentration of chlorophyll-α, and suspended particulate matter during the time study period were 1.7 m, 4.56 NTU, 10.8 μg/l and 27.7 mg/l, respectively. Discharges are received from four major rivers: the Hillsborough River (HR), the Alafia River (AR), the Little Manatee River (LMR), and the Manatee River (MR). All are highly controlled by manmade reservoirs. Chen *et al.* found the two largest rivers, AR and HR to be the dominant CDOM sources to most of the bay and absorption by this pigment rather than by phytoplankton to dominate blue light attenuation in the water column throughout the year. The bay is the largest open-water estuary in the state of Florida, covering 1,030 km^2 at high tide with an average 3.4 m water depth. Tampa Bay tides are mixed, showing both diurnal and semidiurnal depending on the declination of the moon. Over 128 km of deep-water shipping channels, the largest 13 m deep, enables the bay for the operation of three international ports [14]. Lewis and Whitman [15] defined seven sub-regions, although four cover most of the area and are commonly used in regard to bay analysis. These are: Old Tampa Bay (OTB), Hillsborough Bay (HB), Middle Tampa Bay (MTB), and Lower Tampa Bay (LTB).

The bay receives the drainage from a 5,700 Km^2 watershed [14] within which the city of Tampa, the second largest metropolitan area of Florida and the 21th largest in the United States is located, with a growing population of more than 2,500,000 inhabitants [16]. Primary treated waste water was discharged to the bay until 1978, causing eutrophication and consequent decline of seagrass cover [17]. However, since 1979 with the upgrade of the Tampa waste water treatment to tertiary level [18] together with other processes of restoration during the 80's, an improvement in water quality and seagrass cover has been taken place.

Figure 1. NASA MODIS MOD09GQ image of Tampa Bay showing the 56 stations monitored by the Environmental Protection Commission of Hillsborough County (EPCEC), the four main sub-regions and the major tributaries. Stations marked in yellow were used in this study while those in red were excluded for not meeting the criteria (see text).



2.2. In situ *Measurements*

Turbidity, depth, and CDOM estimates were collected *in situ* on a monthly basis as part of routine water quality observations by the Environmental Protection Commission of Hillsborough County (EPCHC). The EPCHC conducts its monthly water quality monitoring program at 56 fixed stations in Tampa Bay (and tributaries) since 1974. Our analysis considered the interval 2000 through 2007 (to match the available data from MODIS Terra) and only data from the 33 stations that met the following criteria: (1) match with a cloud-free satellite image of the same day; (2) the pixel covering the station or the one next to it were not mixed with land, bridge or any other surface except water; and (3) had a water depth ≥ 2.4 m to avoid bottom reflectance contamination. Ultimately, 294 turbidity and paired remote sensing observations from 33 stations were selected out of 5,262 (from 56 stations). The 2.4 m depth criterion was chosen following a trial and error method on 414 matching pairs of data that met the first two criteria. The 2.4 m depth threshold yielded a reasonable relationship between turbidity and reflectance that was not improved by further increasing the threshold (Table 1).

The procedure started with 414 pairs of data including those at the shallowest depth (0.4 m) and continued progressively increasing one meter of depth and removing the shallower matching pairs. All relationships were significant at $P < 0.05$. Chen *et al.* [8] followed similar method to chose stations restricted to depths ≥ 2.8 m. For each of the turbidity paired observations, the corresponding value of Secchi depth was compared with that of bottom depth to estimate the risk of obtaining bottom contamination when using 2.4 m depth as the threshold. 11 out of 294 matching pairs resulted having the same value for both parameters thus having bottom contamination. However, removing these pairs from the analysis would not significantly increment the coefficient of determination. On the contrary, this decreases by a greater extent when increasing the threshold to 2.8 m depth. Therefore, it was decided to maintain the 2.4 m criteria and the 294 matching pairs. Moreover, considering that the potential users of this product for this application may not have easy access to *in situ* information of these variables. In contrast, general bathymetry of Tampa Bay is readily available to the public on line (http://topotools.cr.usgs.gov/topobathy_viewer/).

Table 1. Relationships between *in situ* turbidity (NTU) and R_{rs} from MOD09GQ, separated by depth at the moment of taking *in situ* turbidity sample.

Depth in meters	R^2	Equation	n
9.4	0.31	$111.64 \times R_{rs} + 1.5235$	16
8.4	0.11	$70.439 \times R_{rs} + 2.257$	52
7.4	0.19	$107.97 \times R_{rs} + 1.9461$	78
6.4	0.17	$107.07 \times R_{rs} + 2.0427$	104
5.4	0.17	$120.26 \times R_{rs} + 2.041$	144
4.4	0.24	$141.37 \times R_{rs} + 1.7736$	187
3.4	0.24	$139.26 \times R_{rs} + 1.7967$	232
2.4	0.32	$142.28 \times R_{rs} + 1.79.44$	294
1.4	0.23	$131.33 \times R_{rs} + 1.9265$	394
0.4	0.20	$116.53 \times R_{rs} + 2.0798$	414

All bay water samples were collected and analyzed by the EPCHC and adhere to quality control guidelines of the National Environmental Laboratory Accreditation Program (NELAP) and the US Environmental Protection Agency (EPA) (Joe Barron/EPCHC, personal communication). Turbidity was measured with a nephelometric procedure on a Hach Model 2100N turbidimeter according to EPA Method 180.1. The samples were read directly using the meter at room temperature and reported in nephelometric turbidity units (NTU). A Perkin Elmer Lambda 35 spectrophotometer at 345 nm was used to measure water color in PCUs (which is a measure of optical absorbance at that wavelength of water filtered with a 0.45 μm filter) against a standardized Platinum Cobalt curve after filtering samples with a 0.45μm filter prior to analysis. While we fully understand that this pore size allows for smaller particles that affect absorption and scattering to be collected in the filtrate, these are data collected routinely in Tampa Bay that may provide an additional degree of freedom in the analyses.

Depth measurements were taken at the moment of water sample collection using a Hydrolab. Average values of *in situ* data used in this study for the parameters Secchi disk depth, bottom depth, turbidity, concentration of chlorophyll-α, and suspended particulate matter were: 2.1 m, 5.5 m, 3.6 NTU, 5.5 μg/l, and 16.4 mg/L, respectively. Ranges for the same parameters were: 0.4–7.5 m,

2.4–11.6 m, 0.5–15.4 NTU, 0.26–23.9 μg/l, 4–84 mg/l), respectively. Precipitation data were recorded by NOAA at the Tampa International Airport station and downloaded from the Water Atlas [19].

2.3. Moderate Resolution Imaging Spectroradiometer (MODIS) Data

Two satellites launched by the U.S. National Aeronautics and Space Administration (NASA), Terra and Aqua, carry MODIS sensors with 36 spectral channels. Two channels on each sensor provide near-daily observations at 250 m spatial resolution; one in the visible range between 620 and 670 nm (Band 1) and one in the near-infrared between 841 and 876 nm (Band 2). These wavelengths have been widely used to estimate different but related parameters of water quality in coastal areas with the visible imaging channels: turbidity [8,12], suspended sediments [9,12,20,21], light attenuation [3] and chlorophyll-α [12]; and in inland lakes [22]; suspended sediments have also been estimated with the ratio between the near-infrared and visible [2,10,23].

MODIS Terra and Aqua began generating data in 2000 and 2002, respectively. The criteria used to choose the MODIS Terra sensor for this study was the longer data set available. Terra MODIS in general also provided images closer in time to the time of collection of *in situ* data for this Tampa Bay study. The surface reflectance at full spatial resolution on Bands 1 and 2 is made available as atmospherically corrected observations in NASA standard product MOD09GQ. This product is geolocated and provides an estimate of the reflectance at sea level without atmospheric absorption and scattering effect. This is obtained by multiplying the corrected radiance signal detected at the satellite by π and dividing it by the downwelling irradiance detected above sea level.

A detailed process of the atmospheric correction for this product is described by Doxaran *et al.* [10]. The primary input used to obtain this product are MODIS L1B data, which are then corrected for absorption and scattering effect of gases and aerosols in surface bi-directional reflectance and adjacent effect [24]. According to Doxaran *et al.* [10], the resulting product is not corrected for skylight reflection at the air-water interface and although not sufficiently accurate for open ocean applications it is still appropriate for highly reflective estuarine waters. The authors tested this product (MOD09GQ) for use in water under conditions of the Gironde estuary in France using the ratio between the near-infrared and the red part of the spectrum and found it to be operational to quantify suspended particulate matter concentrations. Such concentrations ranged between 77 to 2,182 mg/l. On highly turbid waters the use of that spectral ratio of above-water upwelling radiance has been shown to account for the skylight reflection [25]. It has been reported that about 80% of the reflectance signal in the red wave length and between 70 to 90% in the near-infrared is due to turbid estuarine water [23]. Consequently, Doxaran *et al.* [10], concluded that the accuracy of atmospheric corrections is not critical since the signal recorded over the estuary at the top of the atmosphere on a clear day mainly results from the water contribution.

2.4. MODIS Data Processing

MOD09GQ images of dates matching those of *in situ* measurements were downloaded through Data Pool, an Internet server of the Land Processes Distributed Active Archive Center (LP DAAC) of the US Geological Survey (USGS) [26] and NASA. All images were processed using the MODIS Reprojection Tool (MRT) and ESRI's ArcGIS version 9.3. *In situ* and remotely sensed data were

acquired within 4 hours of each other. A subset of matching pairs selected with shorter time for testing purposes did not improve the relationship. Images with cloud cover and pixels with values outside the valid range specified by the MOD09GQ.005 quality control descriptions (https://lpdaac.usgs.gov) were excluded from the analysis. As previously mentioned, mixed pixels as well as those matching in situ measurements where water depth was < 2.4 m, were considered invalid.

2.5. Variability of Empirical Relationships

Significant variations in reflectance occur independently of suspended particulate matter load [2,10], since reflectance is an "apparent optical property". These variations may happen because of season and time of an observation, or the angle of observation relative to the sun. The effect of solar elevation related to time is a factor that is hopefully minimized by choice of a sun-synchronous orbit of the MODIS sensors. In a highly turbid estuary, Doxaran *et al.* [2] found higher reflectance at equivalent concentrations of suspended particulate matter just after flood conditions. The authors hypothesized that this was the result of changes in optical properties (absorption and backscattering) caused by changes in the composition of the suspended materials in the estuary during the flood. Similarly, in a study conducted in optically complex estuarine water, Woodruff *et al.* [3] theorized that resuspension from the bottom of larger diameter particles after a storm affected the optical properties by reducing the scattering efficiency of the particles, consequently decreasing the response in reflectance .

The he refractive index can also modify optical properties [2]. The variations of refractive index of suspended solids depend on their mineral composition [4], which can vary with the new materials supplied by rivers during peak flow [2]. Precipitation can cause changes in turbidity and in remote sensing reflectance [1]. These are examples of changes in 'inherent optical properties'. Further, high concentrations of suspended matter in Case 2 waters may cause the water-leaving signal in the visible and near infrared channels to be significantly greater than zero, and as a result the aerosol optical depth that is derived from this signal in the near infrared may be overestimated and further continued to an over correction in the visible part of the spectrum [27-29].

Other possible causes of variability in particle size and mineral composition are tidal cycle [30,31]. However, tides in Tampa Bay are mixed, not seasonal [8]. Our study is over a long time period, and the assumption is that there is no tidal aliasing in our dataset. In fact, wind is a factor more important than tides controlling for sediments resuspension in Tampa Bay [32].

The concentration of CDOM also reduces reflectance [3,8] although mostly in the blue and green part of the spectra. Coastal waters feature increased CDOM concentration due to river discharge [5,6]. CDOM may therefore be found in higher concentrations as a result of storm water runoff during and after rain events. Sticky forms of organic matter mediated by aquatic microorganisms may also cause changes in particle size by aggregating particles into bigger particles [33]. This would affect optical properties not just by changing the particle size but also by augmenting absorption due to organic matter. These factors were not directly accounted for in this study mostly because the standard product used here is in the red part of the spectra where CDOM absorption is minimal (decreases exponentially from blue). Nevertheless, we considered the interaction with color of dissolved matter in water, which we assume here as indicator of CDOM.

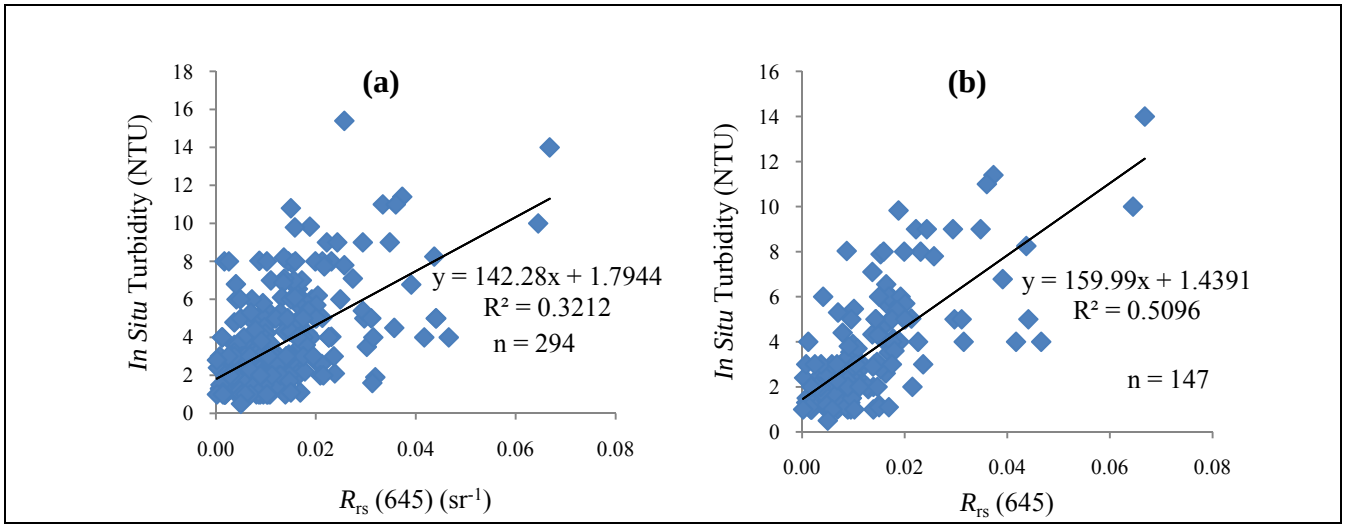
2.6. Algorithm Development

Data from MOD09GQ images in both Band 1 and Band 2 (visible and near-infrared) were analyzed for correlation with matched *in situ* turbidity data from Tampa Bay. After searching for associations with each band separately, ratios between them, and their log transformations; we found the best correlation to be linear between *in situ* turbidity and surface reflectance in Band 1 (Figure 2(a)) with a determination coefficient of 0.32 and 294 matching up pairs of data. The determination coefficient found with *in situ* suspended particulate matter concentration was slightly lower (0.28) but the count of *in situ* data available for matching for this parameter was less than half of that for turbidity (142), therefore that relationship was not further analyzed. After images selection, 161 matching up pairs of data were available for analysis of correlation between *in situ* turbidity and surface reflectance in Band 2, Ratio of Band 2 to Band 1, and log transformations of the ratio Band 2 to Band 1. The determination coefficients for these relationships were respectively; 0.014, 0.013, and 0.0014).

The relationship between the 294 matching up pairs of data (satellite and *in situ*) that met all the criteria was further analyzed controlling for number of days after rainfall (number of days without rain). The matched-up pairs of data were separated in groups according to the number of days without rain at the date of data retrieval. Days when some rainfall was recorded at the Tampa International Airport rain gauge represent day zero. In each case, at least 30 matching pairs (n = 30) were required in the analysis as a representative population, and data were assumed to be normally-distributed. The maximum reached was 8 days after rainfall. Coincidentally, the number of matching pairs for first and last day (days zero and 8) was 34 (n = 34). The iterative relationship for each day of the interval (0 to 8) used the total 294 match-up pairs of data (n = 294). Although the rainfall was measured at Tampa International Airport, it was assumed to represent rainfall in the Tampa Bay region. The average rainfall recorded for pairs showing 'day zero' was 0.9 cm (SD = 0.4 cm). *In situ* data from days with higher rainfall were unfortunately eliminated for not having cloud free images to be matched with.

An additional analysis was conducted to estimate possible effects associated with CDOM. By trial and error, the 294 *in situ* measurements meeting the criteria for valid data were analyzed for the color in Pt-Co units at 345 nm that would yield the best correlation between *in situ* turbidity and surface reflectance. The assumption was that matching pairs with smaller concentrations of organic particles smaller than 0.45 μm would show lower color levels in Pt-Co units at 345 nm (*i.e.*, less optical absorbance), and would therefore be those data points that would show better correlations between *in situ* estimated turbidity and remotely sensed reflectance. The total of 294 samples had color values ranging from 2 to 25 Pt-Co Units of Color at 345nm. Higher correlations were obtained when the dataset was limited to color values ranging from 4 to 7 Pt-Co, which included 147 out of the 294 matching data pairs. The stations generating all the matching data were distributed fairly evenly across the four sub-regions of Tampa Bay (Figure 1) and throughout the study period (2000–2007).

Figure 2. Relationships between *in situ* turbidity (NTU) and R_{rs} from MOD09GQ when considering **(a)** all the matched up pairs available and **(b)** when selecting only those pairs with a filtered sample color reading ranging between 4 and 7 Pt-Co units.



3. Results and Discussion

In situ turbidity at the sampling stations selected according to the criteria described in the methods ranged between 0.5 and 15.4 NTU, with an average and standard deviation (SD) of 3.4 and 7.1 NTU, respectively. There was a positive linear relationship between *in situ* turbidity and R_{rs} from MOD09GQ, except for data retrieved the day of rainfall (day zero) (Table 2). The strength of the relationship tended to increase with the number of days after last rain. The coefficient of determination improved from no relationship when considering the 34 pairs of matching data for 'day zero' (turbidity = 12.053 × R_{rs} + 2.269) to 0.76 when considering the 34 matching pairs for 8 days after rainfall (turbidity = 165.93 × R_{rs} + 1.213), and was significant for all cases with one or more days after rainfall ($P < 0.01$). Figure 2 shows a comparison between *in situ* turbidity and R_{rs} at day 8th or more after a rainfall (Figure 3(a)) and at day zero (Figure 3(b)). Clearly, atmospheric effects due to specific types of aerosol such as smog and dust, and thin clouds and water vapor would increase errors in the surface reflectance retrievals because they are not sufficiently accounted for in the standard atmospheric correction algorithms. The analysis of these possible sources of error was outside the scope of this study since our objective was to assess the feasibility of using this NASA standard product.

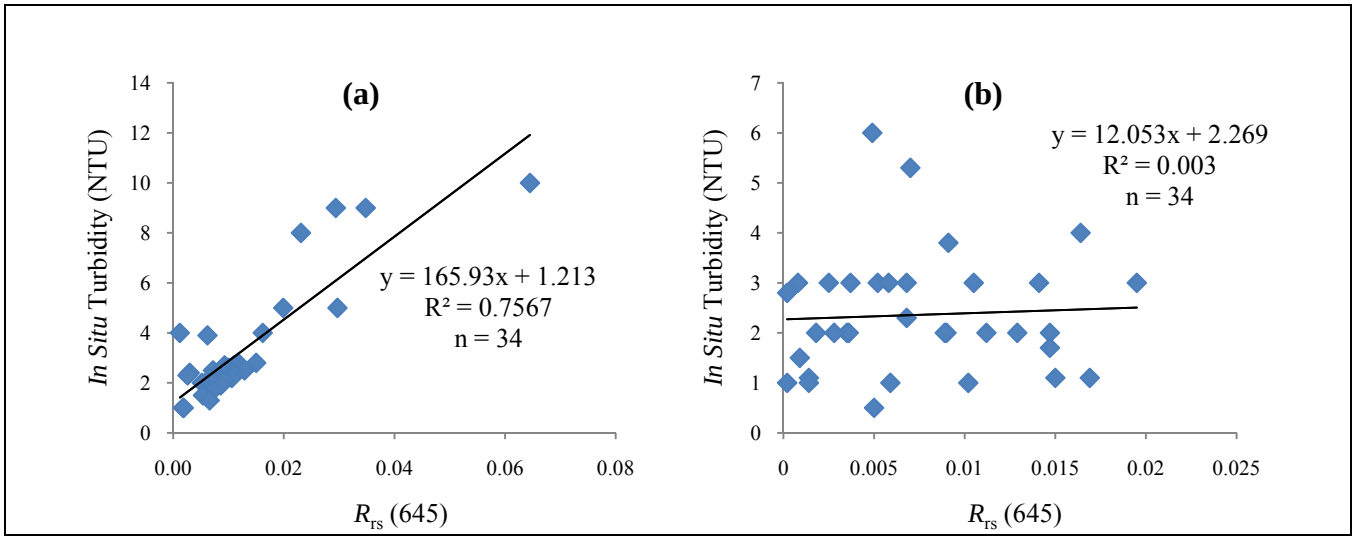
Days with heavy rainfall were typically not included in the study due to clouds. Nevertheless, a t-student analysis found *in situ* turbidity retrieved at day 8 or more to be slightly higher than that retrieved at the day when a low intensity rainfall was reported ($P = 0.04$). Tampa Bay watershed is highly urbanized [34]. Urban areas have greater proportion of soil covered with the impervious layer of roads, parking lots, and roofing causing less erosion of soil matrix and minerals, and a more diluted water runoff. Additionally, storm water retention ponds are very common through out the entire area. These ponds work as sedimentation traps and normally would only overflow after unusual heavy rainfall, which is not the case of days with good quality images used in our study. These factors may help explain why there was not higher turbidity during days with some relatively low intensity of

rainfall (day zero, Table 2). Similarly, the lag time required for runoff to reach the bay (as opposed to direct deposition of clear rain water) may be further increased by the dams in some of the main tributaries of Tampa Bay. These dams periodically open gates and release water into the bay but such discharges not necessarily coincide with rainfall events. Contrary to what would had been expected from the slight but still significant difference in turbidity, no clear difference was detected between reflectance signal at 8 or more days and that of day zero ($P = 0.07$). The fact that a lower turbidity on day zero did not coincide with a lower reflectance supports the possibility of limitations associated with atmospheric correction under those conditions of days when rainfall was reported.

Table 2. Relationships between *in situ* turbidity (NTU) and R_{rs} from MOD09GQ, separated by the number of days after rainfall event. All relationships were significant ($P < 0.01$).

Number of Days	Average Turbidity NTU	Average Turbidity NTU	R^2	Equation	n
8	3.2	10	0.76	$165.93 \times R_{rs} + 1.213$	34
7	3.7	8.2	0.60	$142.86 \times R_{rs} + 1.88$	26
6	4.3	11	0.33	$164.5 \times R_{rs} + 1.9602$	27
5	5.8	14	0.57	$168.38 \times R_{rs} + 3.7513$	27
4	2.8	8	0.30	$153.91 \times R_{rs} + 1.3496$	19
3	3.3	11	0.18	$105.99 \times R_{rs} + 1.7543$	62
2	3.5	8	0.32	$154.27 \times R_{rs} + 1.5501$	27
1	3.5	15.4	0.38	$138.7 \times R_{rs} + 1.6969$	38
0	2.4	6	0.00	$12.053 \times R_{rs} + 2.269$	34

Figure 3. *In situ* turbidity (NTU) *vs.* R_{rs} from MOD09GQ. **(a)** Data collected 8 days after a rain event. **(b)** Data collected day zero (cloud free sky).



Although, explanation regarding turbidity from runoff provided in section 2.5 may not hold here for day zero due to reasons explained above, still the gradual improvement observed in the coefficient of determination with days after rain seems to fit well with a gradual settling of particles brought during

rainfall. New material supplied with storm water runoff should not be excluded as a possibility but also direct wet deposition of solids previously suspended in the atmosphere and/or new particles very near the surface. Similarly, water vapor and thin clouds (that will be dissipated with days after rainfall) may have affected the reflectance of day 0, leading to failure of simple empirical models. Dissolved inorganic and organic nutrients in rain water (direct wet deposition) [35,36] might also have an effect in the relationship between *in situ* turbidity and remotely sensed reflectance signal through the stimulation of phytoplankton.

Figure 4(a) shows a cloud free image derived the same day of rainfall. A homogeneous coloration through out the bay indicate uniform reflectance signal, which may not necessarily correspond to even turbidity if there is not good correlation between the two variables. A better stratification of colors and a higher turbidity toward the shoreline can be appreciated in Figure 4(b). Figure 4(c) shows higher turbidity in LTB and especially in HB, which is consistent with the summary statistics in Table 3 and the higher correlation between turbidity and reflectance signal for these for sub-regions shown in Figure 4.

Figure 4. Maps of turbidity derived from MODIS MOD09GQ data. Data for each map correspond to only one image derived within the time interval 2000–2007 and the relationships indicated in Table 2. **(a)** August 24th, 2004; zero days after rainfall. **(b)** November 8th, 2004; 4 days after rainfall. **(c)** November 1st, 2000; 8 days after rainfall. White color within Tampa Bay represents the mask of shallow water (bottom depth < 2.4 m).

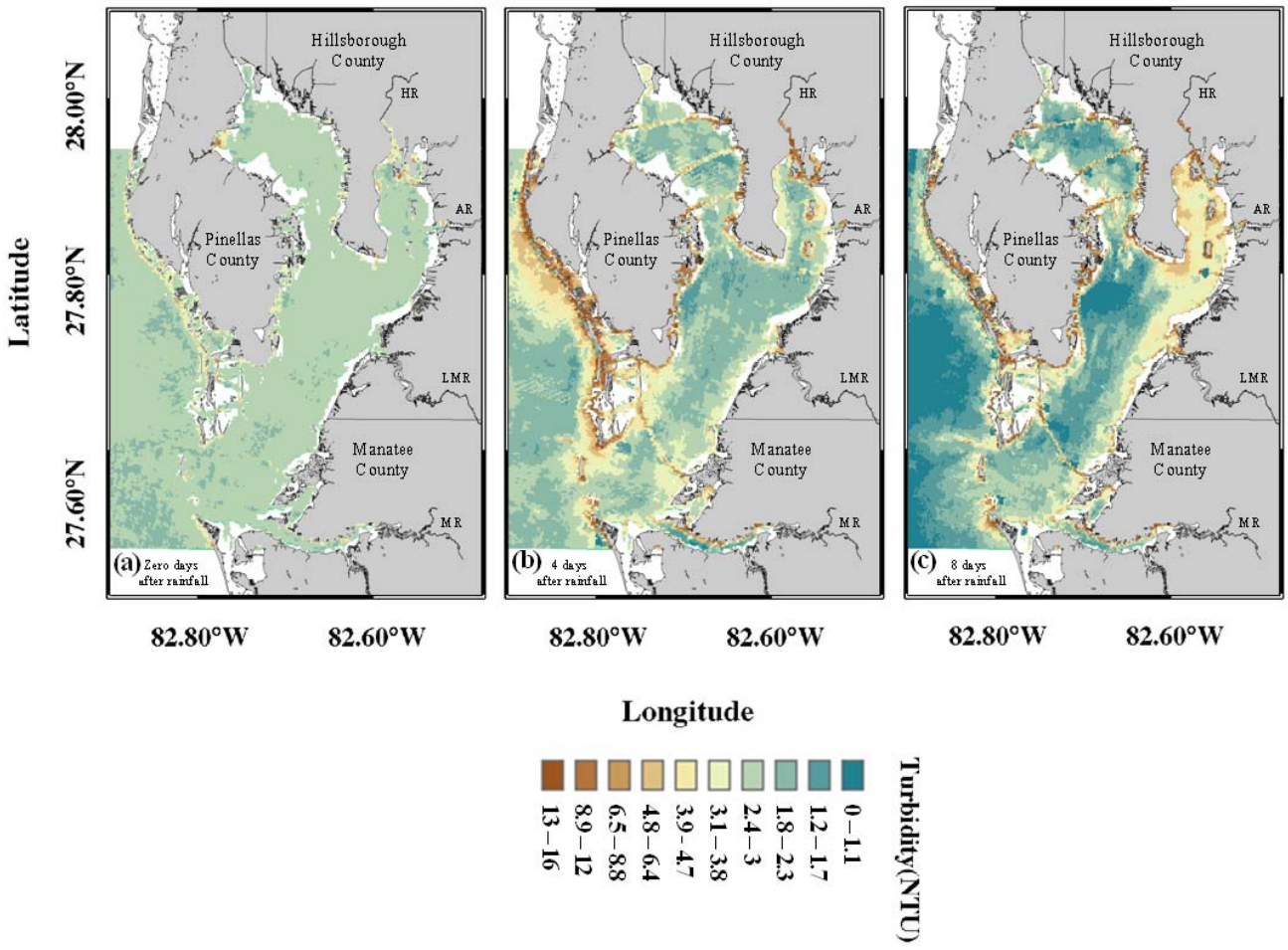


Table 3. Summary statistics of *in situ* data variables used in this study for the time period 2000–2007 by sub-region.

Sub-Regions	Average Turbidity (NTU)	SD-Turbidity (NTU)	Average Bottom Depth (m)	SD-Bottom Depth (m)	Average Color (Pt-Co Units)	SD-Color (Pt-Co Units)	n
HB	4.8	3.0	3.8	1.0	10.0	5.4	38
OTB	2.9	2.2	3.5	1.0	8.7	3.7	37
MTB	3.2	1.9	6.1	2.0	8.3	4.5	112
LTB	3.8	2.6	6.4	2.4	4.7	2.3	107

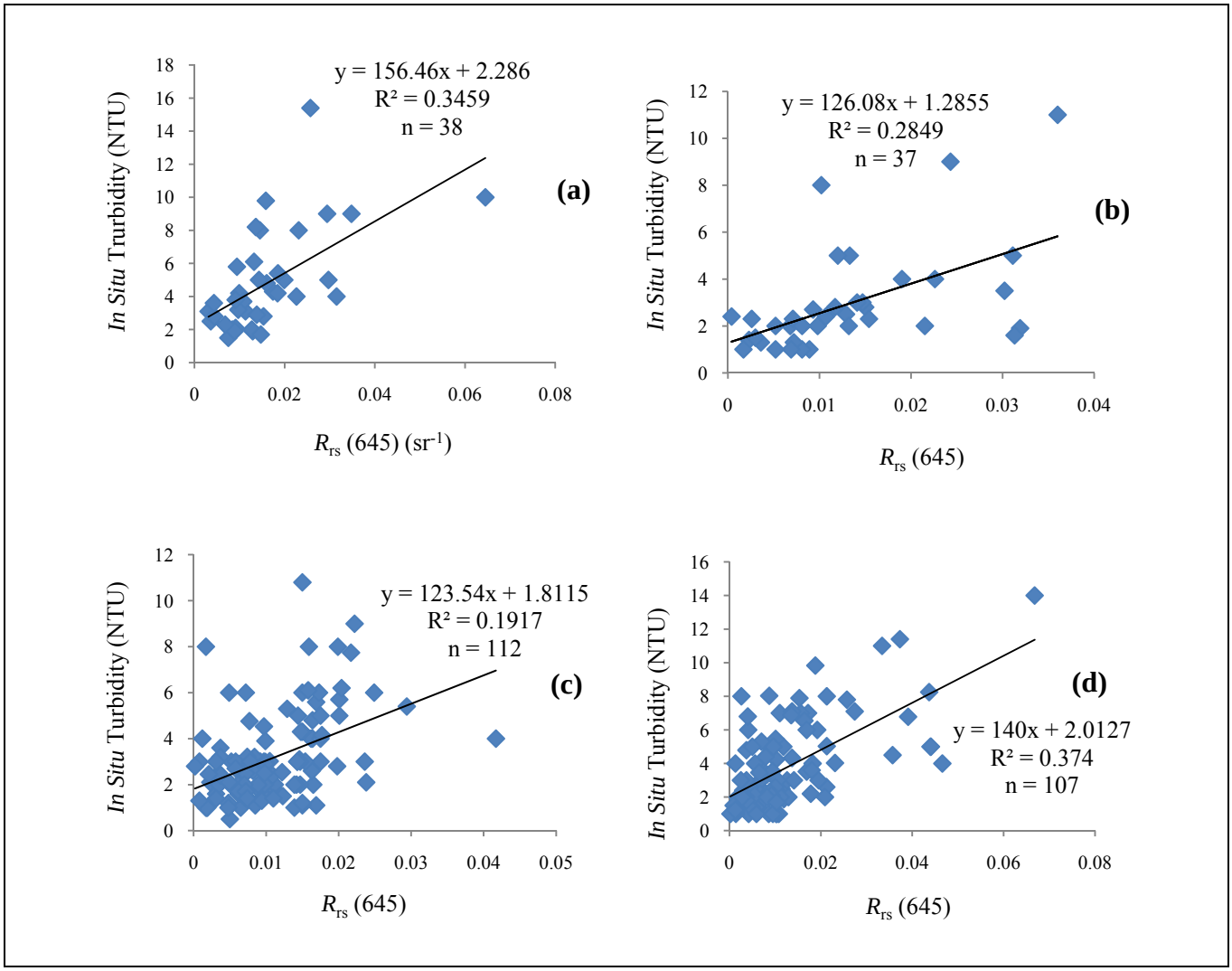
When analyzing each one of the 33 stations separately and using all the available data per station regarding less of the time after rainfall, it was not possible to establish invariant empirical relationships among the 33 stations. They ranged from a coefficient of determination of zero at station 60, 58, and 50 and a coefficient of determination of 0.86, 0.77, and 0.66 in stations 68, 14, and 7. Figure 2 shows the linear relationship between *in situ* turbidity and R_{rs} from MOD09GQ when using (a) all the 294 matched up pairs meeting the first three criteria for this study (see section 2.2.) and (b) the same relationship when using only the 147 pairs with *in situ* samples with a filtered water color reading at 345 nm ranging from 4 to 7 Pt-Co Units (see section 2.6.). Although the coefficient of determination increases from 0.32 to 0.51 (turbidity = 159.99 × R_{rs} + 1.4391) this may be due in part simply to the lower number of pairs used in the second case. In fact, a t-student analysis showed no significant difference between the reflectance signals of both data sets ($P > 0.05$). Furthermore, the correlation at day zero did not show any improvement when reducing the amount of matched up pairs from 34 (total number of pairs at day zero) to only the 23 with filtered sample color range between 4 to 7 Pt-Co Units (results not shown). This again suggests that color due to dissolved constituents does not influence the correlation between *in situ turbidity* and R_{rs} significantly at this wave length (620–670 nm), which is to be expected since the absorption of CDOM decreases in red exponentially from blue.

Table 3 shows the summary statistics per bay sub-region for turbidity, bottom depth, and color of the 294 *in situ* observations that were matched with satellite data for the time period between 2000 and 2007. When comparing the data sets of each sub-region with each other using t-student tests, turbidity in HB showed to be higher than all other sub-regions. Turbidity in LTB (the second highest) was significantly higher than that of OTB ($P < 0.05$). The higher turbidity of HB and LTB may be due to the input of suspended sediments from Hillsborough and Alafia rivers into HB, and influence of wave action and estuarine circulation effects closer to the Gulf of Mexico in LTB. The higher turbidity in HB and LTB coincided with the higher coefficient of determination between *in situ* turbidity and reflectance of these sub-regions as compared with OTB and MTB (Figure 5). These coefficients of determinations were obtained disregarding the number of days after rainfall (due to the low number of matching pairs available for some time lengths).

Analysis with t-student analyses shows significantly higher filtered sample color in HB as compared to MTB and LTB, and no significant differences compared to OTB (95% confidence). This higher reading of filtered sample color in HB and OTB may be in part explained by the influence from Hillsborough and Alafia rivers into HB and its enclosing further inland and more distant from the less

colored water of the gulf. This would be in agreement with literature indicating higher levels of CDOM due to rivers influence [3,4].

Figure 5. Relationships between *in situ* Turbidity (NTU) and R_{rs} from MOD09GQ by bay sub-region and considering all matched up pairs available (regarding less of days after rainfall). **(a)** HB, **(b)** OTB, **(c)** MTB, and **(d)** LTB.



4. Conclusions

Turbidity data collected operationally in Tampa Bay was examined to assess the utility of deriving an analog index from remotely-sensed satellite data. A robust positive linear relationship was found between the MODIS surface reflectance product MOD09GQ band 1 (620–670 nm) and *in situ* turbidity. This relationship, however, varies with the time elapsed after a rainfall event; tending to improve gradually as time increases. *In situ* turbidity retrieved 8 days after rainfall was slightly higher than at day zero, with differences not significant for reflectance and just barely significant for turbidity. The correlation between reflectance signal and *in situ* turbidity increased with time after rainfall presumably because atmospheric effects due to aerosols and water vapor associated with rainy days (which are not properly accounted for in the standard atmospheric correction algorithms) dissipate with

time after rainfall. Alternatively or in addition, the gradual settling down of new particles very near the surface, which may be supplied directly by wet deposition of solids.

With one or more days after rainfall, correlations were slightly improved when only using data within a particular range of filtered sample color. However, no significant difference was detected between the reflectance signal of the total data set and the subset with the selected lower level of filtered sample color. The fact that correlations at day zero were not improved when adjusting by filtered sample color seems to suggest that dissolved colored materials in runoff don't interfere with the reflectance signal.

In situ turbidity and its relationship with reflectance signal in HB followed by LTB were higher than in OTB and MTB, in that order. This could be due to the sediments discharged from Hillsborough and Alafia rivers in HB and the turbulence caused by proximity to the Gulf in LTB. Filtered sample color readings were higher in HB and OTB as compared to the outer sub-regions MTB and LTB presumably because of the deeper inland location and consequently greater influence from runoff and rivers.

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