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SPATIO-TEMPORAL CHARACTERIZATION OF MANILA BAY USING OPTICAL WATER TYPE AND WATER QUALITY MAPPING USING SENTINEL-3 OLCI IMAGES

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ABSTRACT:

Optical water type (OWT) classification provides a way to delineate surface waters according to spectral properties caused by optically active constituents. This classification is useful in mapping out spatial variability and describing changes in water quality over time as it uses inherent optical properties to discriminate areas of a water body. We used Sentinel-3 OLCI images from July 2017 to December 2020 to classify OWT in Manila Bay and to generate chlorophyll-a and total suspended matter (TSM) concentration layers using C2RCC algorithm. Nine coastal OWT classes for Manila Bay having consistent presence and spatial distribution seasonally were identified. The most dominant class, OWT 6, (3.50 µg/cm3 chlorophyll-a; 4.93 g/m3 TSM) was concentrated around the central area of the bay, covering as much as 79% of it. Chlorophyll-a and TSM concentrations were higher in the nearshore areas and were decreasing offshore. The class with the second highest concentrations, OWT 7, (9.11 µg/cm3 chlorophyll-a; 26.80 g/m3 TSM) were found near river outlets, where high nutrient and sediment loadings coming from the watershed enter the bay. Lowest concentrations (0.26-0.70 µg/cm3 chlorophyll-a; 0.64-1.10 g/m3 TSM) were found in OWT 1, OWT 2, and OWT 3, all located farthest from the shore, such as the mouth of the bay leading to the open sea. Validation using in situ observations showed that C2RCC produced relatively good estimates for chlorophyll-a concentrations of up to 12 µg/cm3 ($RMSE = 1.71$ µg/cm3). No conclusion was drawn for TSM due to insufficient data.

1. INTRODUCTION

Remote sensing has made monitoring of surface waters more efficient in many ways. With the numerous and still growing number of literatures presenting remote sensing-based methods of deriving water surface features and water quality indicators, a more in depth understanding of the spatial and temporal variability of water quality conditions has been possible. This approach has complemented conventional water quality monitoring techniques such as in situ sampling. This has also allowed us to see a more vivid picture of the biochemical changes and processes happening in aquatic environments and use this information to draw more appropriate and site-specific management measures.

There have been recent efforts to mainstream water quality remote sensing for monitoring of inland and coastal waters in the Philippines. Bio-optical modelling techniques were applied on Landsat 8, Sentinel-2 MSI, and Sentinel-3 OLCI imagery to generate time-series chlorophyll-a (Blanco, et al., 2020) and turbidity maps of Laguna Lake. Optical water type (OWT) classification was also done to delineate water quality zones which served as basis for assessing the distribution sampling stations maintained by environmental monitoring agencies (Multi-platform and Cross-sensor Water Quality Monitoring Project, 2020; Jalbuena & Blanco, 2020).

OWT classification in water bodies is analogous to land cover classification. Classification schemes are more common for terrestrial imagery but has been gaining traction in aquatic applications. OWTs are distinct delineations representing different optical characteristics which may be attributed to optically active constituents in the water (Spyrakos, et al., 2017). Using this classification, we can more easily map areas with similar water quality conditions and, with available time-series data, describe how such conditions change by looking at the changing spatial distribution of the OWT classes.

2. STUDY AREA

Manila Bay (Figure 1) is a semi-enclosed bay located in the southwestern portion of Luzon Island in the Philippines. It is considered one of the busiest bays in Southeast Asia and a hotspot for marine pollution (Sta. Maria, Siringan, Bulos, & Sombrito, 2009). Since the pre-colonial times, it is one of the country's most important portal and a major hub for trade and industry (Jacinto, Azanza, Velasquez, & Siringan, 2006). The bay serves as a catch basin for seven riverine systems, with Pasig River and Pampanga River as two major tributaries (Ringor & Siringan, 2016). Manila Bay has a coastline of 190 km and covers an area of 1080 sq km which can be accessed through the southern (Caballo Island) and northern (Corregidor Island) channels (Taniguchi, et al., 2008). The bay is bordered by coastal towns in Metro Manila and the Provinces of Bataan, Pampanga, Bulacan, and Cavite (DENR Environmental Management Bureau, n.d.). It supports a huge fisheries and aquaculture industry in these areas, accounting for 11.16% of national production by volume in 2019 (Philippine Statistics Authority, 2019).

Water pollution in Manila Bay is carried by the contributory river systems draining into it. Major urban areas such as Metro Manila, which has a dense population, contributes sewage and other domestic wastes that find their ways into small canals that lead to major rivers and tributaries. Effluents from nearby industries also add to these wastes, causing decreasing dissolved oxygen in the water which may eventually kill aquatic life. Disposal of synthetic toxic wastes have also contributed to high levels of heavy metals (Hosono, Su, Amano, & Onodera, 2010; Prudente, Ichihasi, & Tatsukawa, 1994) in some of the river systems draining into Manila Bay. Rapid expansion and urbanization and poor urban planning has resulted in declining water quality in the bay. Some studies (Ringor & Siringan, 2016; Vallejo, Aloy, Ocampo, Conejar-Espenido, & Manubag, 2019) reported several issues such as eutrophication, pollution, sedimentation, land reclamation, and changes in marine biodiversity in various parts of the Manila Bay. Submarine groundwater discharges (SGDs) were also found to be an important source of nutrients into the bay. Contamination of terrestrial groundwater could result to SGDs bringing in nutrient inputs from fertilizers and sewage (Taniguchi, et al., 2008; Ringor & Siringan, 2016), as well as heavy metals (Hosono, Su, Amano, & Onodera, 2010; Sy, et al., 2017) from land sources. Increased in nutrients could cause harmful algal blooms (Azanza, et al., 2004; Furuya, et al., 2005) affecting shellfish and humans who consume this seafood.

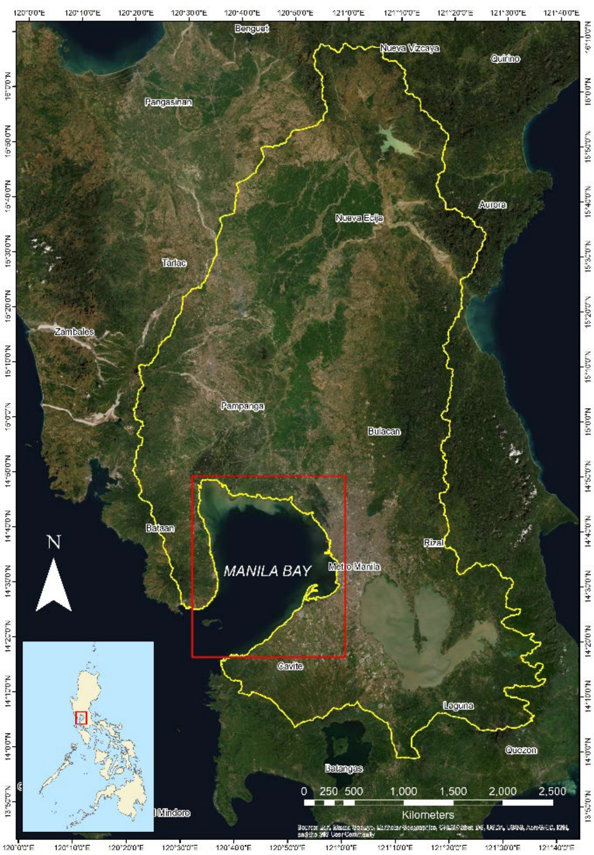

Figure 1. Manila Bay and its watershed (yellow)

3. MATERIALS AND METHODS

3.1 Data Used

Sentinel-3 is one of seven Copernicus missions operated by the European Space Agency (ESA). It is a twin satellite system composed of Sentinel-3A launched in February 2016 and Sentinel-3B launched in April 2018. They provide monitoring data on sea surface topography, sea and land surface temperature, and ocean and land color for applications like ocean forecasting systems, environmental monitoring, and climate monitoring. Sentinel-3 satellites carry four sensors, one of which is the Ocean and Land Color Instrument (OLCI), which was designed bases on Envisat’s MERIS instrument. Datasets are at 300 m resolution in 21 spectral bands (European Space Agency, n.d.).

Sentinel-3 OLCI images acquired from July 2017 to December 2020 were used to generate C2RCC-derived chlorophyll-a and total suspended matter (TSM) and OWT classes for Manila Bay. These images were visually inspected so that only those with minimum cloud cover over Manila Bay were considered. Level 1 images were used as input for C2RCC, while Level 2 full resolution ocean color, water, and atmosphere parameters (WFR) images were used for OWT processing. Sentinel-3 OLCI Level 2 image is a water-only image that is already atmospherically corrected and radiometrically calibrated. All images were downloaded from the Copernicus Online Data Access website.

3.2 OWT Classification

The OWT Classification tool is also available in SNAP. Sentinel-3 OLCI Level 2 images were first reprojected and the subset for Manila Bay was extracted. Coastal OWT was selected. This OWT classification type could identify nine classes based on the distinct standardized spectral clusters of mean reflectance spectra derived from more than 1010 datasets from more than 250 diverse aquatic systems studied by Spyrakos, et al. (2017).

Monthly OWT layers were generated from single-date outputs by applying cell statistics. The most frequently occurring OWT class (i.e., mode) at each pixel location was chosen as the monthly OWT class for that location. Using zonal statistics, chlorophyll-a and TSM concentrations were computed for each OWT class from corresponding OWT, chlorophyll-a, and TSM monthly composites. Final values were determined from the time-series outputs based on the median of the minimum, maximum, and median concentrations of all monthly layers from July 2017 to December 2020.

3.3 C2RCC Processing

The Case-2 Regional CoastColour (C2RCC) processor is a tool developed by applying neural networks to invert radiative transfer simulations to retrieve inherent optical properties (IOPs) of water constituents from Sentinel-2 MSI and Sentinel-3 OLCI images (Brockmann, et al., 2016). This tool is available in Sentinel Application Platform (SNAP) toolbox. It is based on the original work of Doerffer and Schiller (2010) and generates chlorophyll-a and TSM concentration layers as outputs, among others. It can also be used on MERIS, MODIS, VIIRS, and SeaWIFS data.

Processing Sentinel-3 OLCI data in C2RCC is straightforward. Reprojection of the Level 1 image was done before using the subset image of Manila Bay as input. Default parameters (Table 1) were used except for salinity, sea surface temperature (SST), ozone, and air pressure at sea level. Salinity was based on Jacinto, et al. (2006); annual average SST was based on MODIS SST layers; and annual ozone and air pressure were annual average values available in meteorological websites.

Monthly composites of chlorophyll-a and TSM layers were generated from single-date output layers by calculating the median value per pixel location. Median was chosen instead of the mean because it is less sensitive to outlier values which could result from cloud-contaminated pixels.

3.4 Validation of C2RCC Results

We validated C2RCC-derived chlorophyll-a and TSM layers using in situ measurements acquired by Project MapABLE. The Project conducted field surveys in Manila Bay twice or thrice

a month, on days with expected Sentinel-3 overpass. These in situ measurements were acquired using a data logger, a deployable instrument that releases light and records fluorescence from phytoplankton and backscatter from suspended particles in the water. The recorded responses from optically active constituents are converted into chlorophyll-a and turbidity values, respectively, by the instrument.

Parameter	Description	Value
Valid-pixel expression	Defines what pixels are valid while marking invalid pixels as no data	!quality_flags.invalid && (!quality_flags.land || quality_flags.fresh_inland_water)
Salinity	Value entered for salinity of the study area	32.6 PSU
Temperature	Value entered for water temperature (SST) of the study area	Annual average SST
Ozone	Value entered for ozone if not provided by auxiliary data	Variable
Air Pressure at Sea Level	Value entered for surface air pressure at sea level if not provided by auxiliary data	Variable
TSM factor bpart	TSM conversion factor for total back scattering	1.72
TSM factor bwit	TSM conversion factor for back scattering (white/large)	3.1
CHL exponent	Chlorophyll exponent factor	1.04
CHL factor	Chlorophyll factor multiplied to inherent optical property-apig raised to chlorophyll exponent	21
Threshold rtosa OOS	Out of scope threshold for gas corrected top-of-atmosphere reflectances	0.005
Treshold AC reflectances OOS	Out of scope threshold for atmospherically corrected reflectances	0.1
Threshold for cloud flag on transmittance down @865	Threshold for cloud test based on downwelling transmittance @865	0.995
Atmospheric aux data path	Path to the atmospheric auxiliary data	<blank>
Alternative NN Path	Alternative path for other neuronal nets	<blank>

Table 1. C2RCC processing parameters used

4. RESULTS AND DISCUSSION

4.1 OWT in Manila Bay

Sentinel-3 OLCI bands Oa04 (490 nm) and Oa06 (560 nm) are useful for chlorophyll retrieval. High reflectance in these bands suggest presence of phytoplankton species in the water. Spectral responses in bands Oa05 (510 nm) and Oa08 (665 nm) provide combined responses due to chlorophyll, other photosynthetic pigments, and suspended matter in the water. Band Oa07 (620 nm) helps in detecting sediments, which means reflectance in this band corresponds to the turbidity.

We found all nine coastal OWT classes to be present in Manila Bay. Spectral curves for sample pixels from each OWT (Figure 2) showed OWT 1, OWT 2, OWT 3, and OWT 4, which could be observed in the offshore areas of Manila Bay, closest to the mouth, have low reflectance spectra in the blue (bands Oa04 and Oa05) and green (band Oa06) regions, suggesting low chlorophyll-a concentration in these areas. OWT 7, OWT 8, and OWT 9 have the highest peaks in the green and red regions, as well as in the wavelength range between them where band Oa07 is located. This means that these three OWT classes have the highest chlorophyll-a and TSM concentrations.

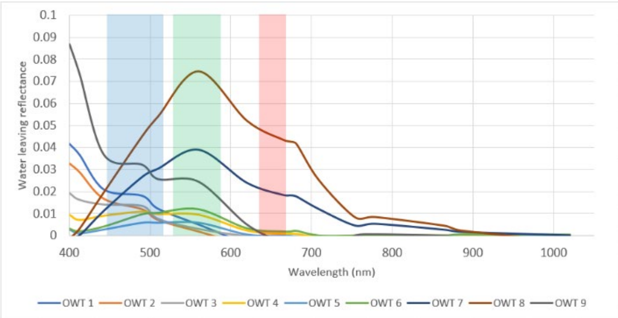

Figure 2. Spectral curves of sample pixels for each OWT

OWT 7 and OWT 9 are commonly found in coastal areas where major river systems meet the bay, with the latter being most pronounced in August, a peak wet season month. OWT 8 is located almost exclusively at the mouth of Pampanga River, which is flows through the largest river basin in the Manila Bay watershed. It only becomes present in other areas, such as off the coast of eastern Bataan, Bulacan, and Cavite, as well as the outlet of Pasig River, in August. Waters near the coasts directly receive nutrients and sediments carried by surface runoffs from the watershed and the major river systems flowing through them.

OWT 5 is mostly found in the central area of the Manila Bay and covers most of the bay in November and December. OWT 1 and OWT 2 are barely present in all the monthly OWT maps produced, while OWT 3 only appears at the mouth of the bay.

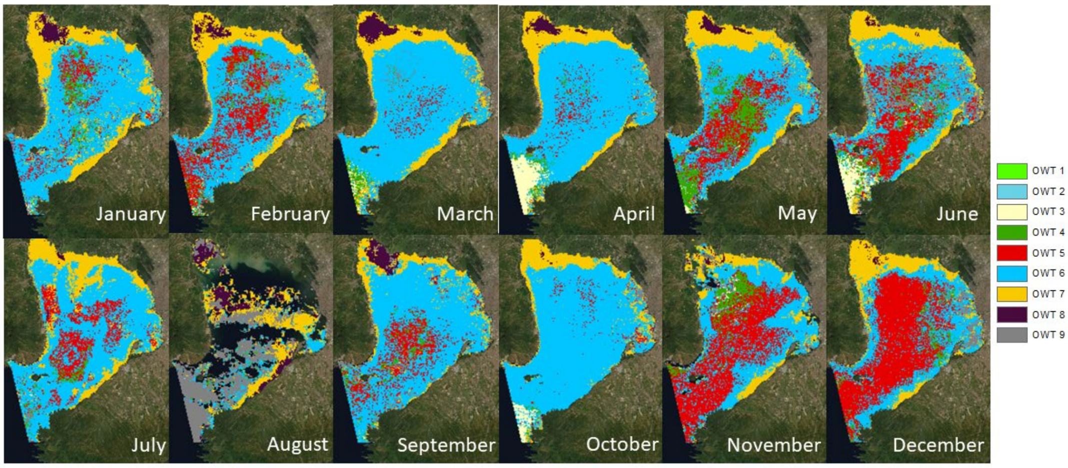

Figure 3. OWT classes in Manila Bay for 2019. OWT 7 is consistently present in the nearshore areas where the major river systems meet the bay. OWT 6 dominates the bay for most of the year except during transition between the seasons. OWT 8 is almost exclusively found at the mouth of Pampanga River except in August.

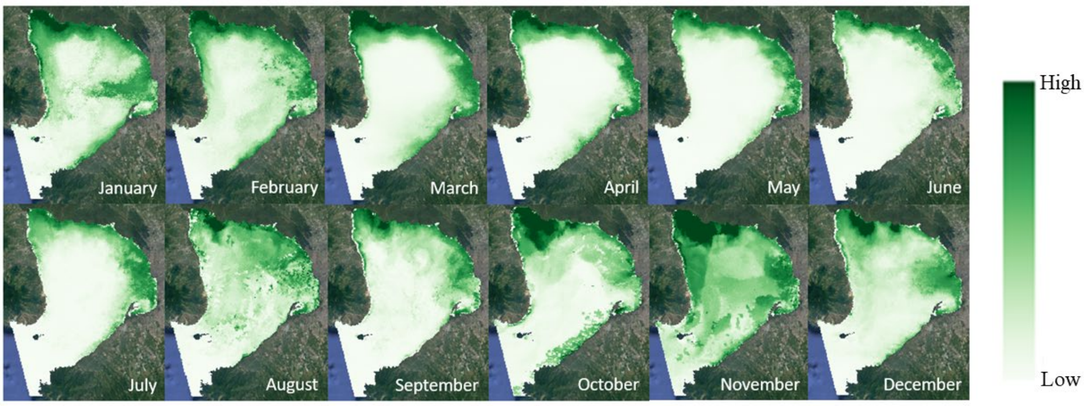

Figure 4. Chlorophyll-a distribution in Manila Bay for 2020. Darker green areas indicate higher concentration. High values are consistently present in the nearshore areas, but these spread into other parts of the bay during the wet season.

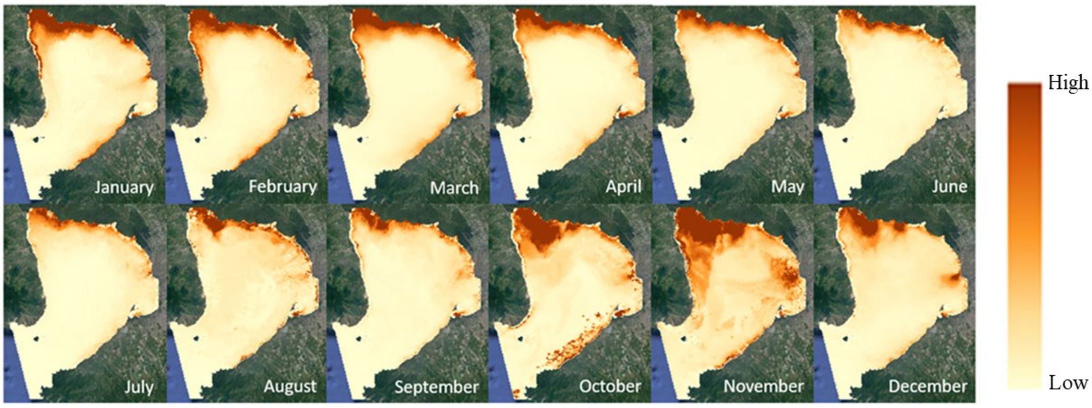

Figure 5. TSM distribution in Manila Bay for 2020. Darker orange areas indicate higher concentration. High values are found in the nearshore areas especially in the northern part of the bay.

4.2 C2RCC-derived Chlorophyll-a and TSM

We processed 309 Sentinel-3 OLCI Level 1 images in C2RCC, resulting in 309 pairs of chlorophyll-a and TSM maps covering July 2017 to December 2020. From these single-date layers, 40 monthly composites each for chlorophyll-a (Figure 4) and TSM (Figure 5) were produced. No monthly composites were generated for August 2018 and August 2019 due to lack of good quality images during these times. August in the Philippines is marked by frequent monsoon rains and typhoons. Satellite images acquired during this month typically contain heavy cloud cover.
For all monthly composite layers for both water quality indicators, we observed high concentrations along the nearshore areas of Manila Bay, especially around the outlets of major river systems draining into it. Chlorophyll-a (as high as 25 µg/cm3) and TSM (as high as 178 g/m3) were consistently highest around the confluence of Pampanga River and Guagua River outlets, in the northeast area of the bay. High concentrations of chlorophyll-a and TSM were also observed to be coming from Pasig River outlet and the shores of Cavite in the eastern side of the bay at certain months of the year. The high chlorophyll-a values observed in the nearshore areas can be explained by the high presence of phytoplankton observed by Vergara, et al. (2017) in monitoring stations near the coast. Their spatial distribution maps for chlorophyll-a from 2012 to 2015 showed that the parameter was concentrated in the northern, northeastern, and eastern parts of Manila Bay (Vergara, et al., 2017). These locations are near tributaries and urban areas where nutrient-rich discharges come from, but the variation in concentration may be due to the amount and type of nutrients received by the bay. These variables are, in turn, dependent on the land use patterns in the watershed (Chang, et al., 2009).

Chlorophyll-a and TSM maps showed similar patterns, in which the concentration decreases farther from the shore. The mouth of bay, which connects it to the open sea, had the lowest concentrations for both indicators (0.01 µg/cm3 chlorophyll-a; 0.04 g/m3 TSM).

The spatial distribution of the two parameters is consistent over the years analyzed. High values are present in the nearshore areas throughout the year, but these are more concentrated in these parts of the bay during the dry season (December-May). Peak dry season months of April and May are characterized by less rainfall, resulting in low discharges coming from the major river systems. With this, there are also lower amounts of nutrients and sediments reaching the bay and these are mostly just retained in the coastal waters.

Chlorophyll-a and TSM become more dispersed to the central portion of Manila Bay during the wet season (June-November). The increase in rainfall during this time causes higher river discharge that carries more nutrient and sediments from the watershed, resulting in even higher concentrations than during the dry season. Since there is more circulation caused by wind and current actions during this season, chlorophyll-a and TSM spread further out into the central and southern parts of the bay. These distribution patterns repeat along with the seasons.

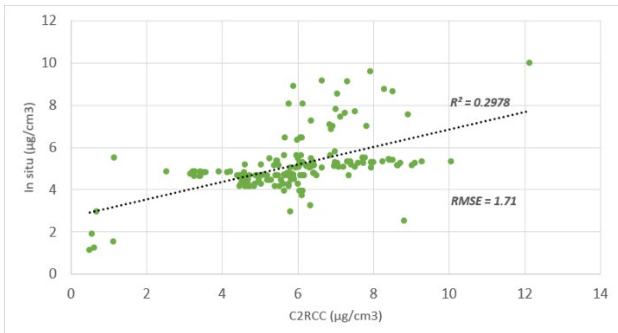

Figure 6. Comparison between in situ and C2RCC-derived chlorophyll-a

The validation (Figure 6) showed that C2RCC provided relatively better estimates ($R^2 = 0.2978$; $RMSE = 1.71$ µg/cm3) for chlorophyll-a concentrations of up to 13 µg/cm3. The low R^2 may be attributed to the low resolution of Sentinel-3 (300 m), whereas in situ observations better capture spatial variability in chlorophyll-a. No conclusion could be drawn for TSM due to very few data points that matched between the in situ observations and the C2RCC results. Note that while field surveys were done during an expected Sentinel-3 overpass, it did not guarantee that a usable image would be acquired over Manila Bay due to cloud cover limitations. Thus, the validation dataset consisted of in situ observations in locations where a C2RCC output was produced for an image that was acquired during a scheduled field survey.

4.3 Water Quality Characteristics of OWT Classes

Results of zonal statistics to calculate median chlorophyll-a and TSM concentrations for all OWT classes (Figure 6) showed that OWT 1, OWT 2, and OWT 3, which are found farthest from the shore have the lowest chlorophyll-a (0.70 µg/cm3, 0.47 µg/cm3, and 0.26 µg/cm3, respectively) and TSM values (1.1 g/m3, 0.89 g/m3, and 0.64 g/m3, respectively). These areas are farthest from any outlet of any river system and, thus, do not directly receive any nutrient and sediment loading coming from the watershed. Because of this, these locations maintain relatively clear water condition compared to the rest of the bay. This is also shown by the sharp decrease in reflectance spectra at around 600 nm and high blue to green ratio, similar to one of the spectral clusters which consisted predominantly of reflectance spectra from coastal waters in the study of Spyrakos, et al. (2017).

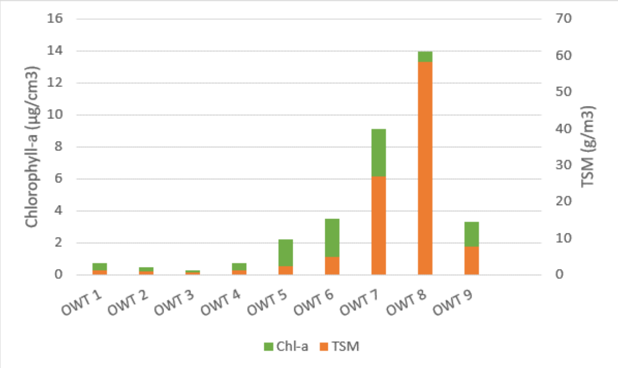

Figure 7. Median chlorophyll-a and TSM concentrations for each OWT class

Time-series water quality layers showed chlorophyll-a and TSM move from the nearshore areas of Cavite in the southeast to the mouth of Manila Bay, leading to the open sea, especially during the dry season. This is likely caused by the circulation of surface waters. Much of the nutrients and sediments in the mouth of bay come from discharges carried by the major river systems of Ylang-Ylang River, Rio Grande River, Imus River, and Cañas River which all flow through medium to high density urban areas in Cavite. Not all of these effluents, however, reach the mouth of the bay, as most are retained in the shores of Cavite.

OWT 4 has an only slightly higher amount of chlorophyll-a (0.76 µg/cm3) and TSM (1.12 g/m3) compared to OWT 1. Spectrally, OWT 1 has a higher response in the blue region than OWT 4, but this reverses in the green region where OWT 4 peaks while OWT 1 drops (Figure 2). This indicates that the spectral response of OWT 1 is mostly driven by chlorophyll, while OWT 4 has a substantial amount of suspended sediments that adds to its detected response. OWT 1 is located almost outside of the bay, an area not directly receiving any sediment from the watershed. OWT 4, on the other hand, is sparsely distributed around the central area of the bay and locations where these are more concentrated tend to change every month. These changes could be due to the circulation of the water around the bay. While OWT 4 can be found also in the mouth of the bay in some months, it is also mixed with OWT 5 in the central area of the bay during the months of June to July, when there is transition from dry to wet season.

Among all classes, OWT 8 has the highest concentrations for both chlorophyll-a (13.98 µg/cm3) and TSM (58.38 g/m3). This class is almost permanently present in the outlet of Pampanga River and tends to cover a larger area further offshore in the northeast Manila Bay in August and September. Pampanga River basin is the largest section of Manila Bay watershed, and the river extends up to the Province of Nueva Ecija in the northernmost area of the region. It flows through a largely agricultural area, carrying nutrients from agricultural runoff, aside from wastewater and livestock activities. At the downstream end of Pampanga River is a large aquaculture area covering three towns, where aquaculture activities are also a large source of nutrients resulting from the use of fish feeds. Sediments loading resulting from erosion and quarrying activities in the northern part of the river basin are also carried along and end up in Manila Bay. All these explain the high chlorophyll-a and TSM concentrations for OWT 8. In August, OWT 8 moves closer to the center of the bay due to changing circulation pattern of the surface water that pushes the high chlorophyll-a and high turbidity waters out from its original location. In the same month, OWT 8 also appears in the outlet of Pasig River and the shores of Cavite as a result of influx of nutrients and sediments brought by the discharges from the watershed.

OWT 7 has the second highest chlorophyll-a (9.11 µg/cm3) and TSM (26.80 g/m3) concentrations. This class covers much of the Manila Bay nearshore areas, especially those where major river systems drain directly. The values are not as high as those of OWT 8 as these other river systems are smaller and flow through a mix of natural and built-up land cover. The aquaculture areas in Bataan, Bulacan, and Cavite are also not as large as those seen in Pampanga.

Spectrally, OWT 7 and OWT 8 have similar curves with peaks at around 560 nm (green) and 710 nm (red edge). As previously mentioned, reflectance in the green band indicates the presence of chlorophyll-a. Spyrakos, et al. (2017) stated that a response around the 700 nm region can be attributed to particulate scattering. Peaks in both these wavelengths in the sample pixels support the findings from the zonal statistics computed. A slightly lower reflectance spectra in OWT 7 than in OWT 8 is also consistent with the computations.

OWT 6 and OWT 9 have almost similar chlorophyll-a concentrations (3.50 µg/cm3 and 3.29 µg/cm3, respectively), but the latter has higher TSM concentration (4.93 g/m3 and 7.69 g/m3, respectively). OWT 6 is the dominant condition in Manila Bay, covering much of the central area in nine out of 12 months and up to 79% of Manila Bay overall. In August, OWT 9 and OWT 7 replace this class, indicating increased sediment loading resulting from increased discharges from the watershed.

5. CONCLUSIONS

OWT classification derived from Sentinel-3 OLCI imagery can be used to elucidate spatio-temporal patterns in water quality conditions. From this study, we found that relatively clear waters with low chlorophyll-a and TSM concentrations are found in the mouth of Manila Bay, farthest from any outlet from the watershed’s river systems. Water quality layers showed that nutrients and sediments coming into this area are transported from the closest outlets in the southeast portion of the bay.

OWT classes with the highest chlorophyll-a and TSM concentrations are found in areas directly receiving discharges from the watershed, and this condition is consistent throughout the year, with some shifting between the highest and second highest concentrations due to changing seasons. The central area of the bay is dominated by OWT classes having the median chlorophyll-a and TSM concentration from all outputs analyzed.

This study is the first attempt to describe Manila Bay water quality conditions in terms of OWT. Because the original work of Spyrakos, et al. (2017) was based on regional datasets which did not include any data from Philippine waters, further studies may be carried out to produce an OWT classification scheme for

Manila Bay using local spectral and water quality data. A more detailed examination on the circulation patterns using hydrodynamic models may also be helpful to further describe the changing patterns in OWT and water quality.

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