MAPPING COLOURED DISSOLVED ORGANIC MATTER IN MANILA BAY USING SENTINEL-3 AND WASI

Manuel, A.[1,2], Blanco, A.[1,2], Cabrera, O. [3], San Diego-McGlone, M.L[4]

[1]Department of Geodetic Engineering, University of the Philippines Diliman
[2]Training Center for Applied Geodesy and Photogrammetry, University of the Philippines Diliman
e-mail: amimanuel@gmail.com, acblanco@up.edu.ph
[3]Institute of Environmental Science and Meteorology, University of the Philippines Diliman
email: olive@iesm.upd.edu.ph
[4]Marine Science Institute, University of the Philippines Diliman
email: msmcglone@upd.edu.ph

KEY WORDS: remote sensing, CDOM, water quality, Manila Bay

ABSTRACT:

Manila Bay is one of the most significant bodies of water in the Philippines; it has abundant natural resources that have been the source of livelihood and center of socio-economic development for centuries. However, Manila Bay is affected by multiple environmental problems and challenges. These include increased organic and nutrient loading from untreated domestic, industrial, and agricultural wastes and deterioration of marine habitats threatened by anthropogenic activities. Regular water quality monitoring is ideal in these situations, however, sampling by traditional field methods would not be enough to assess the spatial and temporal variation of water quality in Manila Bay. Gathering field data for the whole bay can also be very challenging due to its extent and logistic constraints. Remote sensing fills the need for a frequent full view of Manila Bay's water quality. This study makes use of existing bio-optical models to estimate colored dissolved organic matter (CDOM) in Manila Bay. CDOM is the mixture of organic molecules from decayed higher plants, algae, and bacteria, and is the colored portion of the total dissolved organic matter. Sentinel-3 images with concurrent field sampling on 19 July 2021 was used to calibrate and validate the bio-optical models implemented in WASI. The parameterization output showed an R^2 = 0.579 and RMSE of 1.274 m^{-1} from lab-measured CDOM fluorescence converted to absorption. The same parameter set was used on a different image with a concurrent water quality survey on 19 May 2021 and resulted to an R^2 of 0.72 with the spectrofluorometer yellow substance concentrations.

1. INTRODUCTION

1.1 Manila Bay

Manila Bay is plagued by multiple environmental problems and challenges. The increased organic and nutrient loading from untreated domestic, industrial, and agricultural wastes in the watershed can lead to further water quality degradation. (Jacinto, et al., 2006). Sustainable water quality management strategies to prevent further degradation needs to be supported by frequent monitoring (Gray and Shimshak, 2011). However, water quality sampling by traditional field methods may not be enough to assess the spatial and temporal variation of water quality in Manila Bay. Aside from being costly, gathering field data from the whole Manila Bay is time consuming due to its extent. Both weather and water conditions can also make it difficult for most boats and shipping vessels to cover large areas of the Bay within one day. Images captured by multi-spectral satellite sensors could addresses the need for frequent overall picture of Manila Bay's water quality. Remote sensing can help reinforce the capability of our decision makers to monitor water bodies effectively.

1.2 Colored Dissolved Organic Matter

This study focuses on mapping the Colored Dissolved Organic Matter (CDOM) concentration in Manila Bay using existing bio-optical water quality models implemented through the Water Color Simulator or WASI. CDOM, also referred to as gelbstoff or yellow substance, gilvin, or aquatic humus, is a mixture of organic molecules from decayed higher plants, algae, and bacteria. CDOM is the colored portion of the total dissolved organic matter and absorbs light in the UV-Visible part of the spectrum. It gives water the appearance of yellow to brown color based on its amount. (Carder et al., 1989). The light absorption of CDOM affects the light available to phytoplankton communities and is also crucial to studying carbon dynamics in surface waters. (Hoge, et al., 1995). It is commonly measured in the field through its absorption and fluorescence properties (Kowalczuk et al., 2009)

1.3 Remote Sensing of CDOM

As the optically active part of the total dissolved organic matter, CDOM can be detected with remote sensing satellite sensors (Kutser et al., 2017). CDOM is commonly measured from satellite images as the absorption coefficient (m^{-1}) in a reference wavelength. The absorption coefficient of CDOM is described by Bricaud et al. (1981) by the equation:

$$\mathrm{aCDOM}(\lambda) = \mathrm{aCDOM}(\lambda 0) e^{[-S(\lambda - \lambda 0)]} \tag{1}$$

Wherein a_{CDOM} is absorption coefficient (m^{-1}), λ is wavelength, λ_0 is reference wavelength, and S is the slope factor. The reference wavelengths used to express the amount of CDOM vary from 380 to 440nm. Retrieving CDOM absorption through remote sensing makes use of the central wavelengths in bands between 420-440nm. WASI implementation makes use of λ_0 = 440nm and S = 0.014 nm^{-1} by default which is a good representation for varying water types (Bricaud et al., 1981; Carder et al., 1989).

Sentinel-3 OLCI (Ocean and Land Color Instrument) offers great opportunities for water quality remote sensing as it can provide images with high spectral resolution using images captured almost daily. Since the OLCI was especially built for water monitoring, the amount and location of spectral bands are strategically placed for water quality retrieval methods (Soomets et al., 2019). Sentinel 3 OLCI Bands 2 and 3 with central wavelength at 412.5 and 442.4 nm, respectively have specific significance when retrieving yellow substances. Toming et al. (2017) was able to assess in-situ measurements of CDOM with empirical algorithms calculated from Sentinel-3 (also atmospherically corrected with C2RCC). The correlation between the calculated values from band ratios and field data varied from 0.35 to 0.63, showing that Sentinel-3 atmospherically corrected data can produce good estimates of different water quality parameters, including CDOM.

Mapping and monitoring of CDOM in coastal waters are important. It has applications for drinking water, inland water ecology, radiative heating, and carbon global cycle studies. Remote sensing enables us to get CDOM information with temporal frequency and the coverage needed (Kutser et al., 2017).

1.4 Bio-optical Model Inversion

Modeling the relationships between bio-optical water quality parameters and remote sensing reflectance is a long process and mostly requires deep knowledge on the interactions between light and water. This also requires an extensive library of in situ data and running simulations that may require high computing resources (IOCCG, 2006).

Inverse modelling used in remote sensing of water bodies first retrieves the Inherent Optical Properties (IOPs) from the radiance and distribution spectrum. A common issue with inversion of these known relationships between bio-optical water quality parameters from the remote sensing reflectance is the ambiguity of its results; different sets of parameters can result from the same spectral shape (Kutser et al 2017). The inversion is a two-step process: first, the retrieval of IOPs from radiance, then proceeds with the retrieval of biogeochemical parameters from these IOPs. Both are of these inexact procedures and can produce ambiguous results, which is why spectral inversion must be done with caution and data from field missions (IOCCG, 2006).

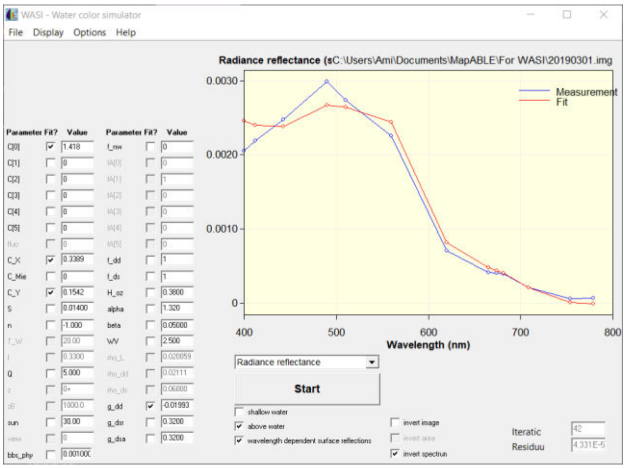

Figure 1. Sentinel-3 Bio-optical Water Quality Inversion through the Water Color Simulator (WASI)

In this study, bio-optical models by Albert and Mobley (2002) implemented in WASI by Gege (2014) will be used to map out CDOM in Manila Bay. WASI is ideal for application on inland water bodies but it may also be used for oceanic and coastal applications.

2. DATA AND METHODS

2.1 Field Water Quality Surveys

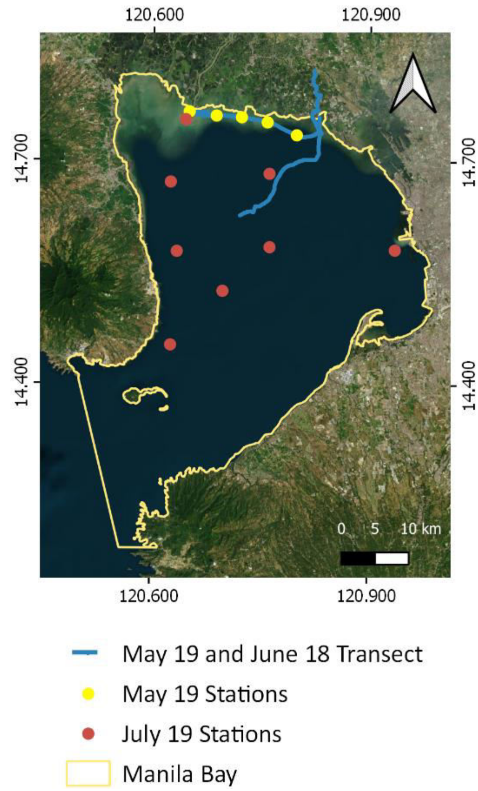

Figure 2. Water Quality Field Survey Points and Route (2021)

Sentinel 3 images with concurrent field sampling on May 19, June 18, and July 19 2021 were used to calibrate the bio-optical models implemented in WASI. Field data was collected using a bbe Fluoroprobe which measures CDOM as Yellow Substance (ug/L), a correction factor for the other phytoplankton classes. For the July 19 field survey, we were also able to collect water samples that were later measured in the lab for CDOM in Normalized Fluorescence Units (NFU).

Flow-through data from transects were available for May 19 and June 18 field dates. July 19 only had data available for each station. There is limitation on extent and number of stations due to availability of vessel needed to conduct the surveys.

2.2 WASI Parameterization

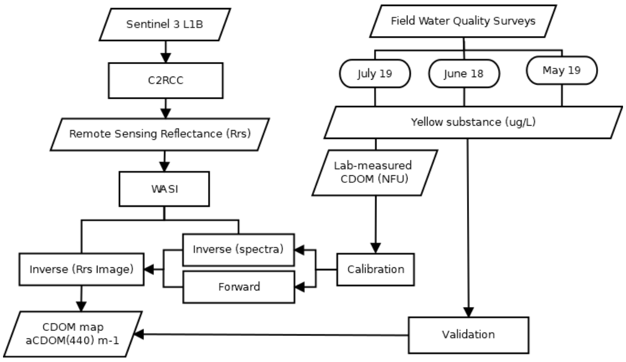

Figure 3. Workflow for calibrating WASI to map Manila Bay CDOM based on field data

Figure 3 shows the general workflow done to produce CDOM maps from Sentinel 3 images and WASI. Sentinel 3 L1B data atmospherically corrected with C2RCC was used instead of Sentinel L2 data. This was chosen due to errors in pixels from bands 1-2 of Sentinel-3 L2 having negative reflectance values affect the inversion process of WASI. The lab measured CDOM values in NFU were converted to a_{CDOM} using the equation from Ferrari and Dowell (1998):

$$aCDOM(\lambda) = 0.54(\pm 0.036) + 0.125(\pm 0.037)Fn(\lambda) \quad (2)$$

where $a_{CDOM}(\lambda)$ is the absorption coefficient and $Fn(\lambda)$ is the fluorescence in NFU measured at a specific wavelength. These were then input to the forward spectra mode for WASI, and the parameter sets were used as a starting point in calibrating the final set for mapping CDOM. Field data from June 18 and May 19 were used to validate and assess the resulting CDOM maps.

3. RESULTS AND DISCUSSION

WASI outputs CDOM in absorption per meter (m^{-1}) units does not directly translate to the yellow substance measured by the fluoroprobe in ug/L. Previous studies show that the relationship of fluoroprobe yellow substance (ug/L) to CDOM absorption and fluorescence measurements vary per instrument, water body, and depth of measurement (Twiss, 2011). The lab measurements from the July 19 field converted into absorption (m^{-1}) units used to calibrate the consequent Sentinel-3 image resulted in an R^2 of 0.579 with an RMSE of 1.274 m^{-1}.

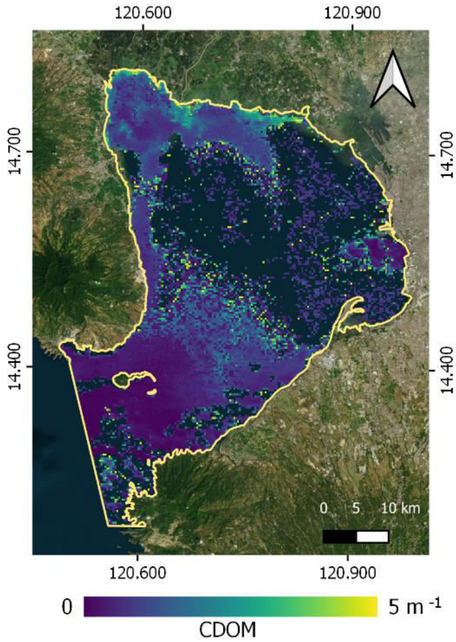

Figure 4. CDOM map using Sentinel-3 image from May 19, 2021

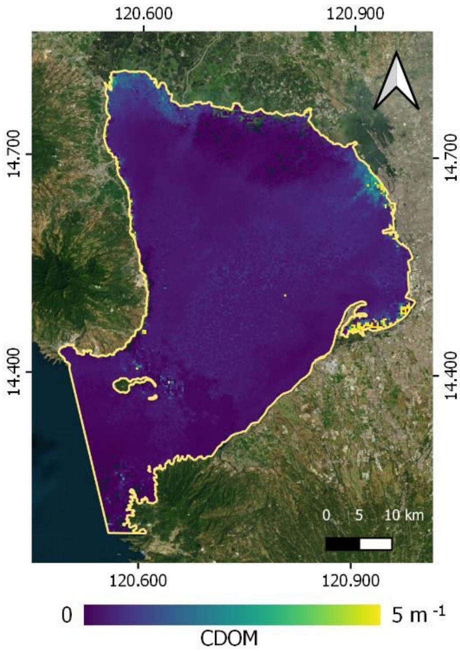

Figure 5. CDOM map using Sentinel-3 image from June 18, 2021

The resulting parameterization for the July 19 Sentinel-3 image was applied to both May 19 (Figure 4) and June 18 (Figure 5) images. As shown in Figure 6, the scatter plot between the CDOM map output and the fluoroprobe yellow substances for the transect showed an R^2 of 0.72. Excluding the flow-through data along the transect and only including the station data of only 5 points, the R^2 is at 0.91.

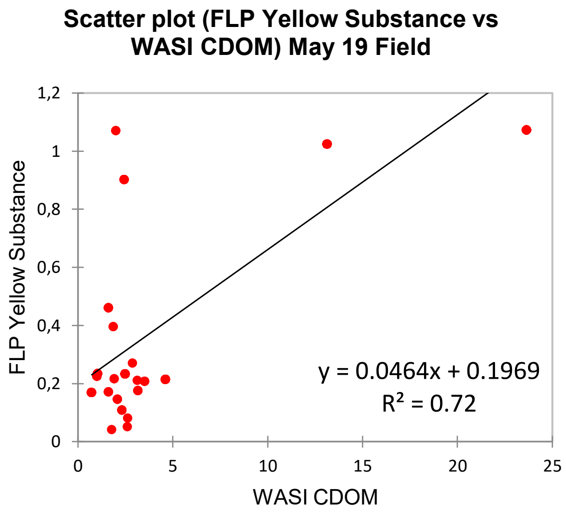

Figure 6. Scatter plot of Fluoroprobe Yellow Substance concentration vs. WASI CDOM output for the May 19 image

The output for the June 18 image however, indicates that the changes in yellow substance measured by the fluoroprobe does not correspond to the changes in CDOM (m^{-1}). This may be due to the small variation of yellow substance (σ = 0.45) measured in the open sea area included at that time. The CDOM map from the May 19 image modeled with the fluoroprobe yellow substance measurements collected near the Pampanga River resulted to an R^2 of 0.72 (Figure 6). The yellow substance measured in the transect near Pampanga River had more varied values (σ = 2.11) compared to those collected on June 18.

These suggest that the yellow substance measured by the fluoroprobe may not be reliable for areas with low CDOM, and that our current parameter set for mapping CDOM with WASI performed well in coastal areas where CDOM was higher.

As seen in Figures 7-9, the northern part of nearshore Manila Bay showed relatively higher concentrations of CDOM than the rest of the Bay. The area (Figure 7) is from Sasmuan Pampanga Coastal Wetlands, fish farms, and Pampanga River. The high concentration of CDOM (up to 23 m^{-1}) in this area may be due to dissolved organic matter from the coastal wetland and inflow from the Pampanga River.

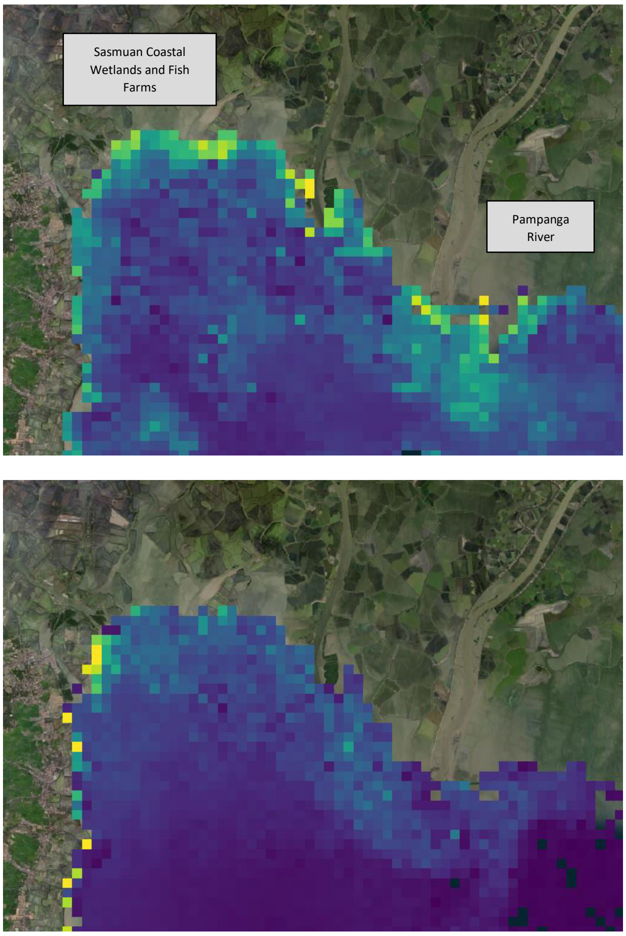

Figure 7. High CDOM Areas near Pampanga River, Sasmuan Pampanga Coastal Wetlands and Fish farms (Top: May 19, Bottom: June 18)

The eastern side of the Bay (Figure 8) shows the high concentration of CDOM near the Las Pinas-Paranaque Critical Habitat and Ecotourism Area, one of the few remaining wetlands in the National Capital Region. High CDOM concentrations (11-15 m^{-1}) can also be seen along Bacoor and Kawit Cavite where which are active fisheries and aquaculture areas. As shown in Figure 9, higher CDOM values are seen near the Navotas Fish Port, Manila Harbor, and the Pasig River with some CDOM pixels values reaching 30 m^{-1}.

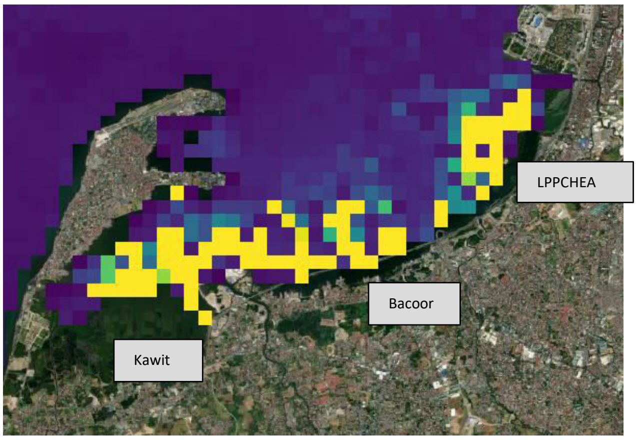

Figure 8. High CDOM areas near Bacoor-Kawit Bay area

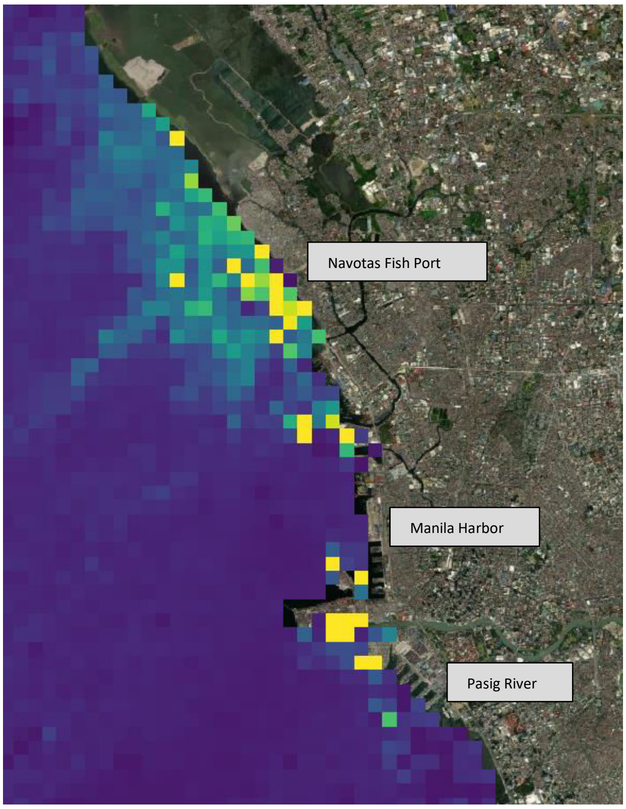

Figure 9. High CDOM areas near Manila Harbor, Navotas Fish Port and Pasig River

4. CONCLUSION

We were able to map out CDOM in Manila Bay using bio-optical water quality models calibrated with field survey data. The calibration data we used gave an R2 of 0.579 with an RMSE of 1.274 m^{-1}. The outputs from the Sentinel-3 image acquired during the dry season (May 19 image) resulted to an R^2 of 0.72, given that the area surveyed on that date was near a major river. We cannot conclusively assess yet how accurate the CDOM estimation is in areas with low CDOM due to the accuracy and precision of the spectrofluorometer for open sea levels. With the resulting CDOM maps, we are able to show its variation for the whole Manila Bay from Sentinel-3 images. This is a huge advantage over field survey that can only show data for few points over periods of time.

ACKNOWLEDGEMENTS

This research was done as a part of the Development of Integrated Mapping, Monitoring, and Analytical Network System for Manila Bay and Linked Environments (MapABLE) Project and the Integrated Mapping, Monitoring, Modelling, and Management System for Manila Bay and Linked Environments (IM4ManilaBay) Program. This project is implemented by the University of the Philippines Training Center for Applied Geodesy and Photogrammetry (TCAGP), funded and monitored by DOST-PCIEERD.

REFERENCES

Albert, A., Mobley, C.D., 2003. An analytical model for subsurface irradiance and remote sensing reflectance in deep and shallow case-2 waters. Optics Express, 11, pp. 2873-2890

Bricaud, A., Morel, A. and Prieur, L., 1981. Absorption by dissolved organic matter of the sea (yellow substance) in the UV and visible domains1. Limnology and Oceanography, 26(1), pp.43-53.

Carder, K., Steward, R., Harvey, G. and Ortner, P., 1989. Marine humic and fulvic acids: Their effects on remote sensing of ocean chlorophyll. Limnology and Oceanography, 34(1), pp.68-81.

Ferrari, G. and Dowell, M., 1998. CDOM Absorption Characteristics with Relation to Fluorescence and Salinity in Coastal Areas of the Southern Baltic Sea. Estuarine, Coastal and Shelf Science, 47(1), pp.91-105.

Gray, W. and Shimshack, J., 2011. The Effectiveness of Environmental Monitoring and Enforcement: A Review of the Empirical Evidence. Review of Environmental Economics and Policy, 5(1), pp.3-24.

Gege, P., 2014. WASI-2D: A software tool for regionally optimized analysis of imaging spectrometer data from deep and shallow waters. Computers & Geosciences, 62, pp.208-215.

Hoge, F.E., Vodacek, A., Swift, R.N., Yungel, J.K. and Blough, N.V., 1995. Inherent optical properties of the ocean: retrieval of the absorption coefficient of chromophoric dissolved organic matter from airborne laser spectral fluorescence measurements. Applied optics, 34(30), pp.7032-7038.

IOCCG, 2006. Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications. Lee, Z.-P. (ed.), Reports of the International Ocean-Colour Coordinating Group, No. 5, IOCCG, Dartmouth, Canada.

Jacinto, G.S., Azanza, R.V., Velasquez, I.B. and Siringan, F.P., 2006. Manila Bay: environmental challenges and opportunities. In The environment in Asia Pacific harbours (pp. 309-328). Springer, Dordrecht.

Kowalczuk, P., Durako, M., Young, H., Kahn, A., Cooper, W. and Gonsior, M., 2009. Characterization of dissolved organic matter fluorescence in the South Atlantic Bight with use of PARAFAC model: Interannual variability. Marine Chemistry, 113(3-4), pp.182-196.

Kutser, T., Koponen, S., Kallio, K., Fincke, T. and Paavel, B., 2017. Bio-optical Modeling of Colored Dissolved Organic Matter. Bio-optical Modeling and Remote Sensing of Inland Waters, pp.101-128.

Soomets, T., Uudeberg, K., Jakovels, D., Zagars, M., Reinart, A., Brauns, A. and Kutser, T., 2019. Comparison of Lake Optical Water Types Derived from Sentinel-2 and Sentinel-3. Remote Sensing, 11(23), p.2883.

Toming, K., Kutser, T., Uiboupin, R., Arikas, A., Vahter, K. and Paavel, B., 2017. Mapping Water Quality Parameters with Sentinel-3 Ocean and Land Colour Instrument imagery in the Baltic Sea. Remote Sensing, 9(10), p.1070.

Twiss, M.R., 2011. Variations in chromophoric dissolved organic matter and its influence on the use of pigment-specific fluorimeters in the Great Lakes. Journal of Great Lakes Research, 37(1), pp.124-131.