University of Puerto Rico at Mayagüez

Department of Geology

Research Tittle:

Impact of Hurricane Maria in the discharge of total suspended matter (TSM) concentrations in the rivers of Puerto Rico as measured by Sentinel-3 Ocean and Land Colour Instrument (OLCI)

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Abstract

On September 21, 2021, Puerto Rico was affected by large amounts of rain. Rainfall led to coastal/urban flooding, landslides, soil eroding, and debris into rivers. The scientific problem of this work is to study the impact of Hurricane Maria in the discharge of total suspended matter (TSM) concentrations in the rivers of Puerto Rico as measured by the Sentinel-3 Ocean and Land Colour Instrument (OLCI). Before Hurricane Maria is expected low concentration of TSM and Chl-a in the rivers. On the contrary, after Hurricane Maria, Sentinel-3 (OLCI), is expected higher concentration of total suspended matter (TSM) and chlorophyll-a (Chl-a). The total suspended matter (TSM) concentrations and chlorophyll-a (Chl-a) were retrieved using the Case-2 Regional Coast Colour (C2RCC) processor for the SentiNel Application Platform (SNAP). The results showed that the hypothesis was accepted because values of TSM concentrations was less than $7\ g/m^3$ and Chl-a less than $10\ mg/m^3$around Puerto Rico before Hurricane Maria. The total suspended matter (TSM) concentrations after Hurricane Maria increased around $30\ g/m^3$ near river discharge. As the sediment moves away from the coast its concentrations decrease approximately $0.143\ g/m^3$. Studying these parameters of water quality is important to protect aquatic ecosystems since the amount of sediment in rivers can degrade water quality. The Case-2 Regional Coast Colour (C2RCC) algorithm provided a useful evaluation of the effects of Hurricane Maria on the discharge of Puerto Rico's rivers. Future work is needed to validate products using in-situ measurements.

Keywords: Sentinel-3 OLCI, Total Suspended Matter (TSM, Chlorophyll-a (Chl-a), Case-2 Regional Coast Colour (C2RCC) processor, Hurricane Maria, Puerto Rico

Introduction

Every year the rivers of Puerto Rico are affected by extreme rainfall generated by atmospheric conditions. Lots of rain bring lots of eroded soil and debris into rivers. Also, the amount of sediment in rivers can degrade water quality. For this reason, the scientific problem is inclined to know the impact of total suspended matter (TSM) concentration and chlorophyll-a (Chl-a) in the rivers of Puerto Rico after an extreme rain event such as Hurricane María. The Sentinel-3 Ocean and Land Colour Instrument (OLCI) will be used to apply the Case-2 Regional Coast Colour (C2RCC) processor for the SentiNel Application Platform (SNAP).

The purpose of this work is to retrieve concentrations of chlorophyll-a (Chl-a) and total suspended matter (TSM) using a large database of simulated water leaving reflectance's and top atmospheric radiances. It is expected that before the event of heavy precipitation will show a low concentration of TSM and Chl-a in the rivers. On the contrary, after a heavy precipitation event such as Hurricane Maria, Sentinel-3 Ocean, and Land Colour Instrument (OLCI), will show a higher concentration of total suspended matter (TSM) and chlorophyll-a (Chl-a). In either case, values of TSM and Chl-a are necessary for understanding the dynamics of water quality and protecting aquatic ecosystems.

Puerto Rico is drained by main basins that form rivers such as, Río Grande de Loíza, Río Grande de Manatí, Río Grande de Arecibo, Río de La Plata, Río Culebrinas and Río Grande de Añasco. (Figure 1) As rivers move downstream, the water current transports sediments as bedload, suspended load (silt and clay), and dissolved load (Figure 2). The silt and clay are suspended due to the turbulence in the flow, and they move at the speed

of the flow. The current carries these sediments across the river, and they are small enough that they never go to the ground; therefore, stay suspended in the water. When we have atmospheric conditions, is imminent the enormous amounts of rain that are received in Puerto Rico, producing floods and large river discharges. A clear example was Hurricane María that impacted the island on September 20, 2017. The total accumulated rainfall from Hurricane Maria, especially in Caguas, totaled almost 38 inches (Figure 3). The amount of rainfall result in increased runoff from the land.

Some studies have been carried out in retrieving water quality of the coastal waters of Puerto Rico using images from the moderate resolution Visible Infrared Imaging Radiometer Suite (VIIRS) satellite to retrieve products of chlorophyll-a (Chl-a) and the diffuse attenuation coefficient at 490 nm (Kd490). Even with the limitations of spatial resolution and loss of data to cloud cover, the 6-year imagery time-series analysis can provide a useful evaluation of the effects of these two hurricanes on the coastal water quality in Puerto Rico and quantify the exposure of benthic habitats to higher nutrient and turbidity levels (Hernández et, al., 2020).

The suspended sediments can determine the quality for aquatic habitats (Bilotta et al., 2008). The total suspended matter (TSM) is a measure of the concentration of particulate material in the surface water such as mud, silt, and other fine-scale debris, including both organic and inorganic fractions (EUMETSAT et al., 2021). Small amounts of sediments carry nutrients that can increase the growth of phytoplanckton, but large quantities can block the sunlight in the water column and limit the growth. Suspended sediments increase scatter light in the Red and the Near-Infrared bands, thus, they are more

reflective. In general, in those two bands, the reflectance contains information about the amount of sediment in the water column.

Sentinel-3 OLCI

The Copernicus Sentinel-3 is an ocean and land mission that has two identical polar orbiting satellites (Sentinel-3A and Sentinel-3B) separated by 180º. The Sentinel-3A was launched on February 16, 2016. Later on, April 25, 2018, was launched the Sentinel-3B. The Ocean and Land Colour Instrument (OLCI) is a medium-resolution imaging spectrometer that use five cameras to provide a wide field view (Figure 4). The OLCI push-broom instrument swath is 1270 km with a global coverage every 4 day (Figure 5). The OLCI swath is tilted 12.6° westwards to mitigate the negative impact of sun-glint contamination.

The Case-2 Regional CoastColour (C2RCC) Processor

The C2RCC processor carefully evaluates the characteristics of the optically complex waters through its inherent optical properties (IOP). In addition, coastal atmosphere is used to parameterize radiative transfer models for the ocean and the atmosphere (Figure 6). A large database of water leaving reflectances is calculated and is used to study how the light interacts with gases and particles in our atmosphere. For that reason, a data base of approximately 5 million cases is generated for different instruments, such as Ocean and Land Colour Imaging (OLCI), Medium Resolution Imaging Spectroradiometer (MERIS), Moderate Resolution Imaging Spectrometer (MODIS), etc.

Once the large data base is available neural networks are trained to perform the inversion of spectrum for the atmospheric correction, i.e. the determination of the water

leaving radiance from the top of atmosphere radiances, as well as the retrieval of inherent optical properties of the water body (Brockmann et al., 2016).

On the other hand, the bio-optical model (Figure 7) uses five components for absorption and scattering to train a neural network. The total absorption is composed of three components: pigment absorption (apig), detritus (ad), and gelbstoff (ag). While, the total scattering is composed of two components, a typical sediment scatter (bp) and white scatter (bw). The white scatter component represents calcareous sediments which is reflected in a corresponding phase function because these are larger particles. As a result, of using arithmetic conversion factors in-water products are available such as, total suspended matter (TSM) concentration, and chlorophyll-a (Chl-a).

The Case-2 Regional CoastColour (C2RCC) processor has been validated in various studies with in-situ data. From Kyryliuk et al. (2019), the remote sensing product of the attenuation coeficient “kd_z90max” retrieve from the C2RCC-SNAP, showed a good correlation with the in-situ data. Other algorithms used in Kyryliuk study need to be tested and refined with more imagery data acquisitions combined with in situ spectra data.

In contrast, this study is focused on the evaluation of the Case-2 Regional Coast Color (C2RCC) algorithm to recover TSM and Chl-a concentrations in the rivers of Puerto Rico.

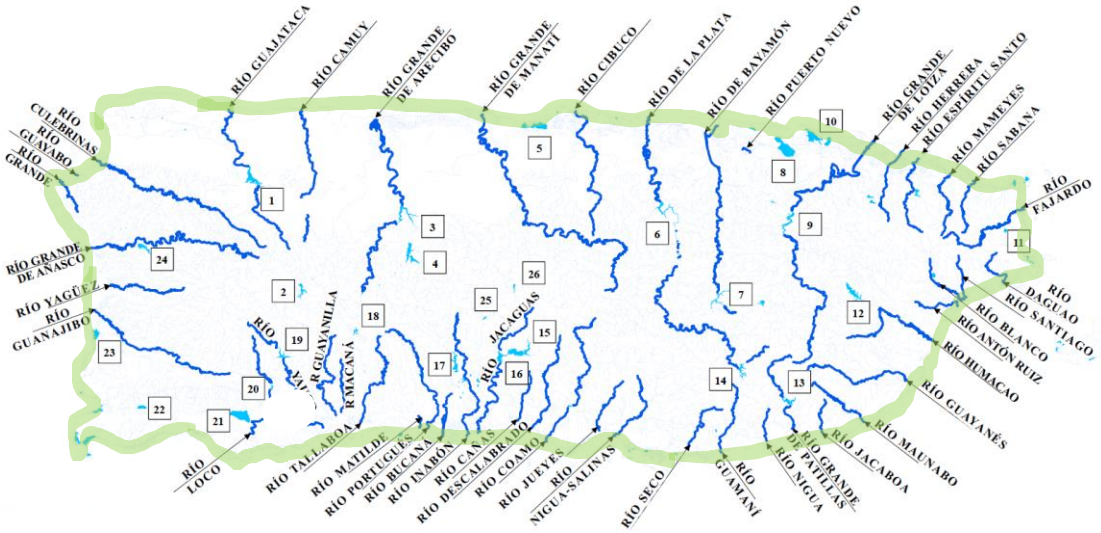

Figure 1: *Main rivers of Puerto Rico (Source: Departamento de Recursos Naturales y Ambientales, http://gis.otg.gobierno.pr/PDF_Maps/Rios_principales.pdf)*

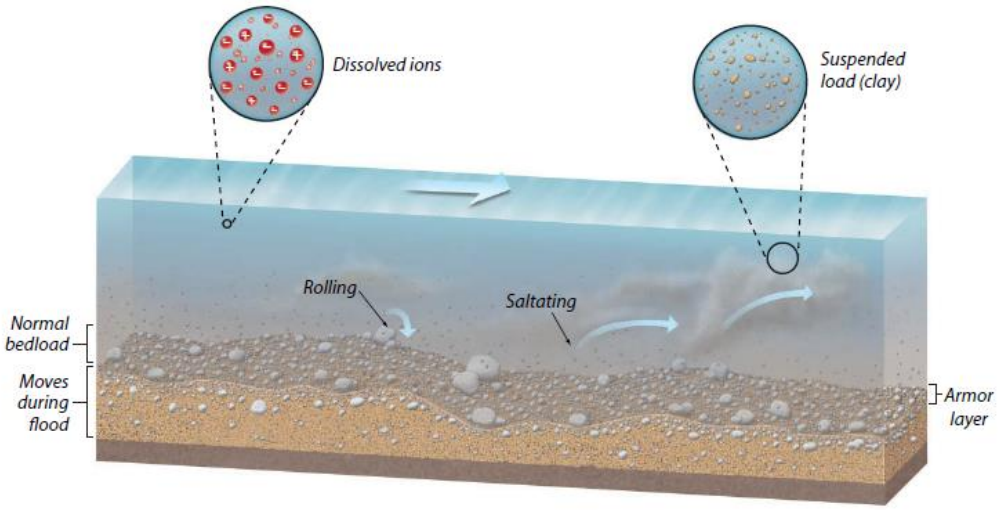

Figure 2*: Streams and rivers carry sediment as bedload, suspended load, and dissolved load (Source: Book Key Concepts in Geomorphology, page 194)*

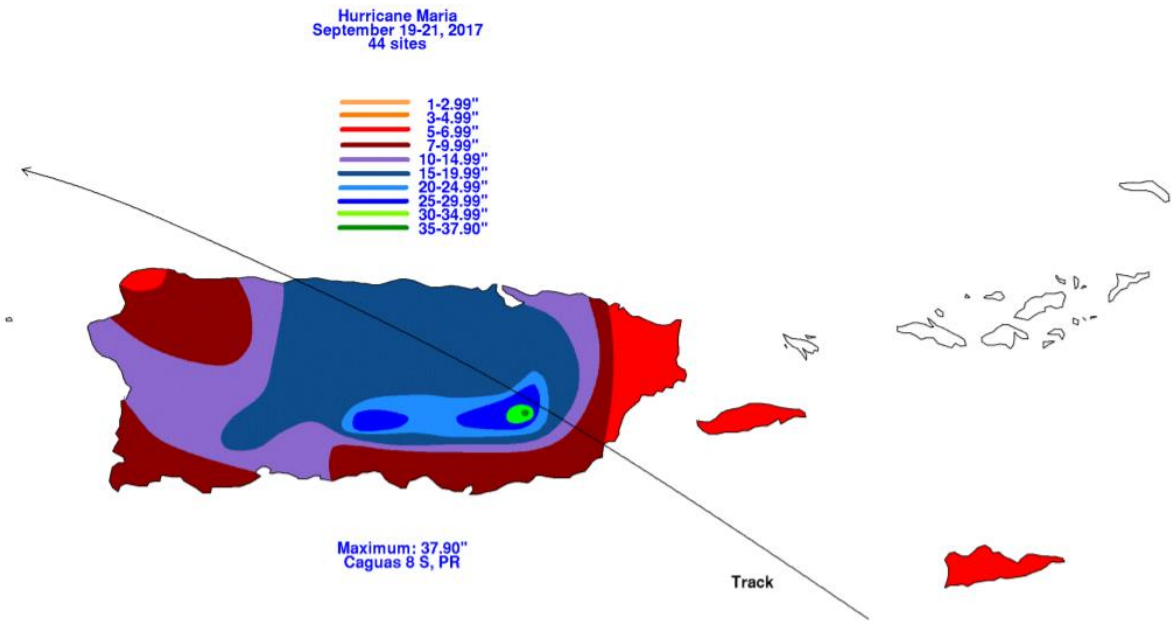

Figure 3*: National Hurricane Center Tropical Cyclone Report shows the storm total rainfall (inches) from Hurricane Maria (Source: https://www.nhc.noaa.gov/data/tcr/AL152017_Maria.pdf page 41)*

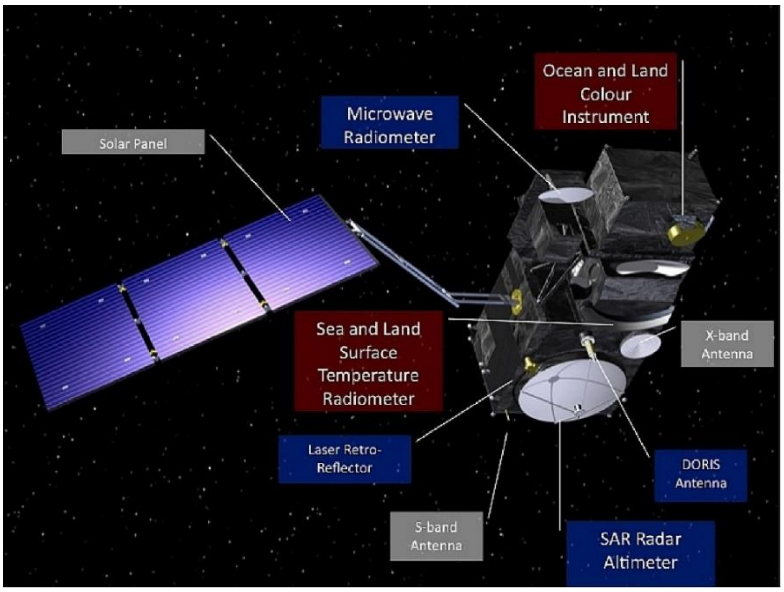

Figure 4: *Main instruments of the Sentinel-3 mission: Ocean and Land Colour Instrument (OLCI), Sea and Land Surface Temperature Radiometer (SLSTR), SAR Radar Altimeter (SRAL), MicroWave Radiometer (MWR). (Source: Copernicus Sentinel-3, https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/copernicus-sentinel-3)*

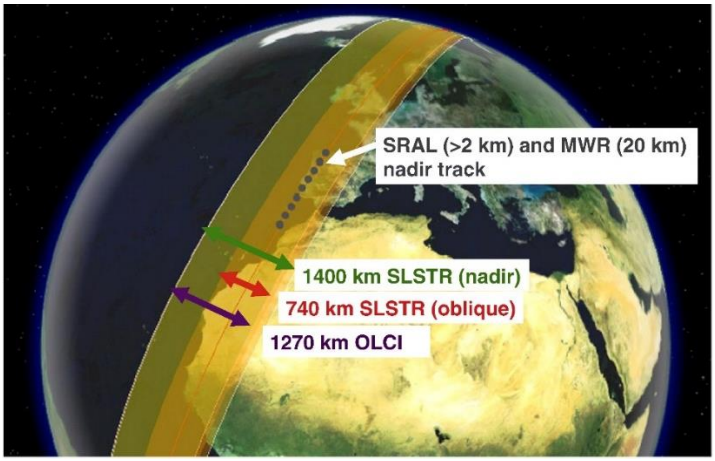

Figure 5*:Geographical Coverage (Source: The European Space Agency, https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-3/satellite-description/geographical-coverage*

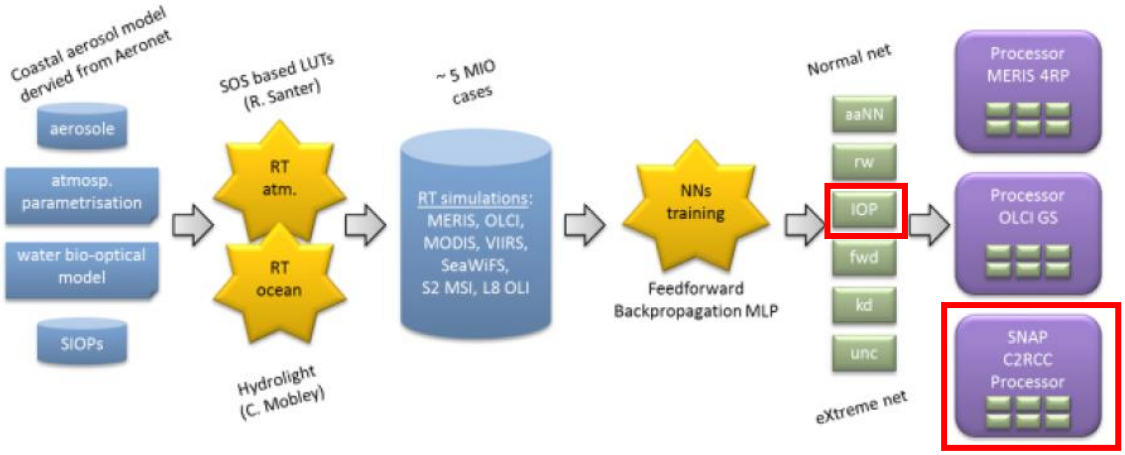

Figure 6: *Schematic of the C2RCC development process (Source:*

http://step.esa.int/docs/extra/Evolution%20of%20the%20C2RCC_LPS16.pdf)

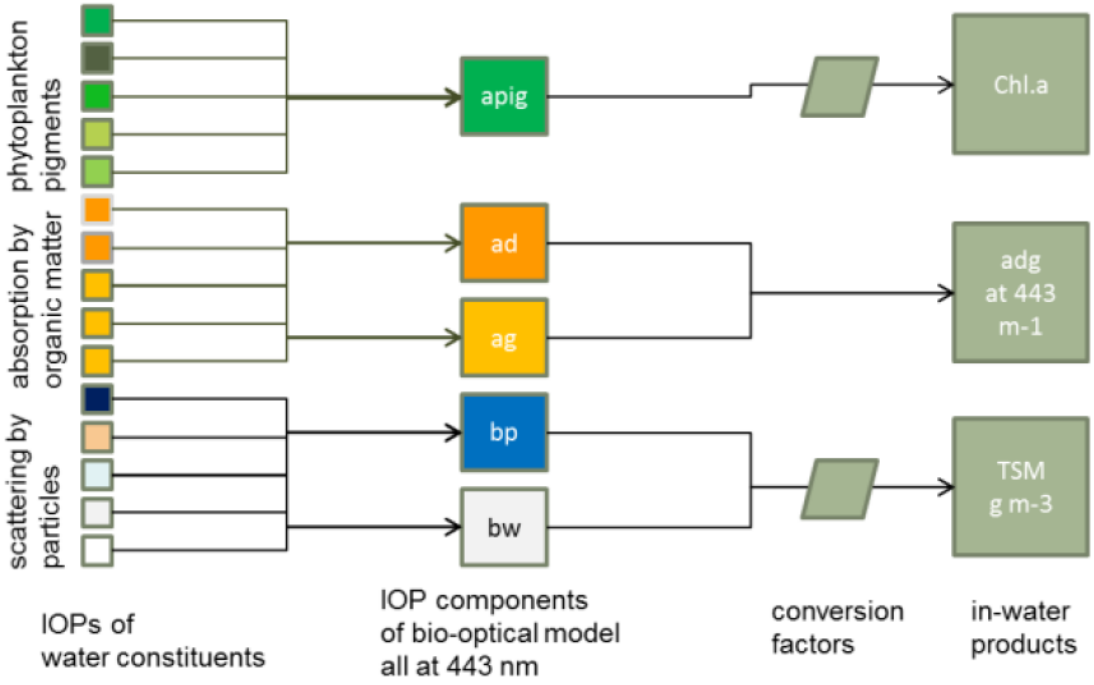

Figure 7: *Inherent optical properties (IOP) components for bio-optical model (Source:*

http://step.esa.int/docs/extra/Evolution%20of%20the%20C2RCC_LPS16.pdf)

Methods

Satellite Images and Pre-Processing

The Sentinel 3 OLCI, with approximately 300 m of full resolution (FR) and a reduced resolution (RR) of 1.2 km, provides a total of 21 spectral bands ranging from the visible (400 nm) to the near-infra-red (1020 nm). Each band is programmable in position and width (Table 1).

First of all, Sentinel-3 Level 1 images were used to study total suspended matter (TSM) concentrations and chlorophyll-a (Chl-a) in rivers of Puerto Rico. The level 1 images represent processed level 0 data to geographically locate radiations from Top-Of-Atmosphere (TOA) for each OLCI channel. Five Sentinel-3A OLCI L1 images were captured before Hurricane Maria on September 18, 2017, and after Hurricane Maria (September 29, and October 4, 7,11, 2017). The satellite images were downloaded from Copernicus Open Access Hub (https://scihub.copernicus.eu/) with 300 m of full resolution (FR).

Second, the software SentiNel Application Platform (SNAP) was used to process the Sentinel-3 OLCI images. For example, the *Subset* tool provided by *Raster Management*, a cut of the image was made for the region of study. The specific product subset with GeoCoordinates were: *North latitude bound* (19.217), *West longitude bound* (-67.432), *South latitude bound* (17.241) and *East longitude bound* (-65.31). (Figure 8)

The Case-2 Regional CoastColour (C2RCC) Processor

The Case-2 Regional CoastColour (C2RCC) processor for the SentiNel Application Platform (SNAP) was used to process the level 1 data to water leaving reflectances and

geographysical variables as cholophyll. As a result, level-2 products were derived of the Ocean and Land Colour Instrument (OLCI) to retrieve total suspended matter (TSM) concentrations and chlorophyll-a (Chl-a).

The Case-2 Regional CoastColour (C2RCC) processor depends on a large database of water leaving reflectances and top-of-atmosphere radiances. The C2RCC focuses on two parts: the atmospheric correction and the in-water. First, the C2RCC algorithm uses a neural network of a large data base to perform the inversion of spectrum for the atmospheric correction. Second, the water leaving reflectances produced by the atmospheric correction neural network is used as input data for the in-water part. Another neural network called IOP (inherent optical properties) NN (neural network) is part of the algorithm to perform the inversion of the spectrum into IOPs. These IOPs are converted into chlorophyll-a and total suspended matter (TSM) concentration.

Band	λ centre (nm)	Width (nm)	Function
Oa01	400	15	Aerosol correction, improved water constituent retrieval
Oa02	412.5	10	Yellow substance and detrital pigments (turbidity)
Oa03	442.5	10	Chlorophyll absorption maximum, biogeochemistry, vegetation
Oa04	490	10	High Chlorophyll,
Oa05	510	10	Chlorophyll, sediment, turbidity, red tide
Oa06	560	10	Chlorophyll reference (Chlorophyll minimum)
Oa07	620	10	Sediment loading
Oa08	665	10	Chlorophyll (2nd Chlorophyll absorption maximum), sediment, yellow substance/vegetation
Oa09	673.75	7.5	For improved fluorescence retrieval and to better account for smile together with the bands 665 and 680 nm
Oa10	681.25	7.5	Chlorophyll fluorescence peak, red edge
Oa11	708.75	10	Chlorophyll fluorescence baseline, red edge transition
Oa12	753.75	7.5	O2 absorption/clouds, vegetation
Oa13	761.25	2.5	O2 absorption band/aerosol correction.
Oa14	764.375	3.75	Atmospheric correction
Oa15	767.5	2.5	O2A used for cloud top pressure, fluorescence over land
Oa16	778.75	15	Atmos. corr./aerosol corr.
Oa17	865	20	Atmospheric correction/aerosol correction, clouds, pixel co-registration
Oa18	885	10	Water vapour absorption reference band. Common reference band with SLSTR instrument. Vegetation monitoring
Oa19	900	10	Water vapour absorption/vegetation monitoring (maximum reflectance)
Oa20	940	20	Water vapour absorption, Atmospheric correction/aerosol correction
Oa21	1020	40	Atmospheric correction/aerosol correction

***Table 1**: OLCI bands characteristics (Source: [User Guides - Sentinel-3 OLCI - Radiometric Resolution - Sentinel Online - Sentinel Online (esa.int)])*

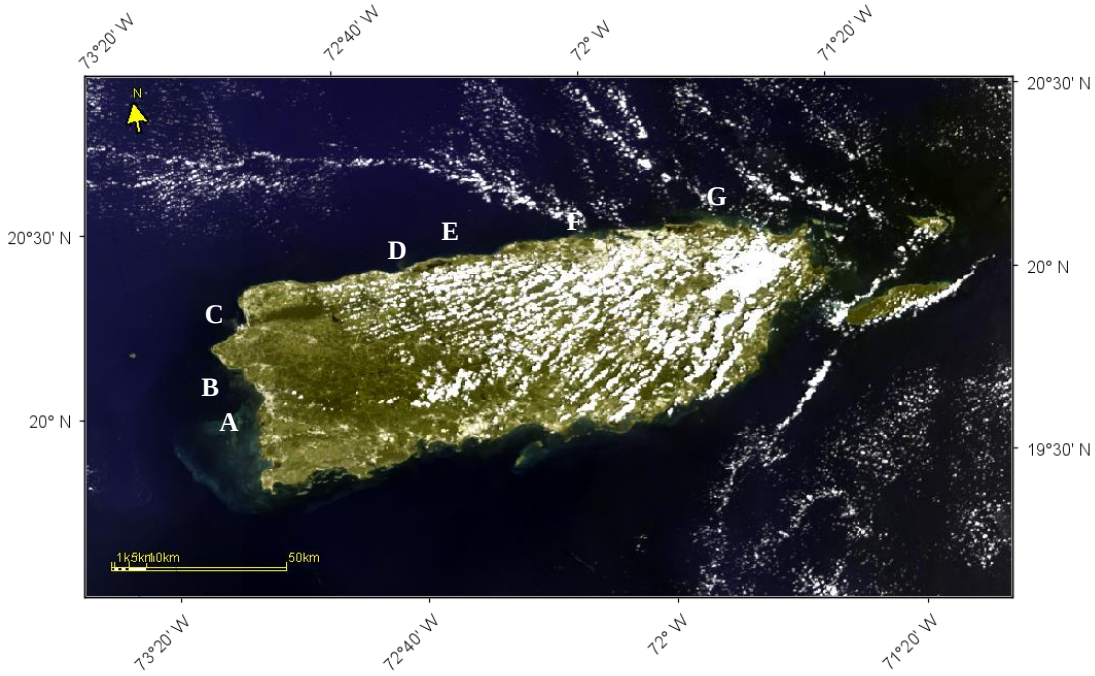

Figure 8: *Sentinel-3A OLCI level-1, captured on September 18, 2017 (before Hurricane Maria), at 2:28 pm, showing the area of study, Puerto Rico. (A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (D)Río Grande de Arecibo, (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza. (Source: SentiNel Application Platform (SNAP))*

Results

Before Hurricane Maria *(September 18, 2017)*

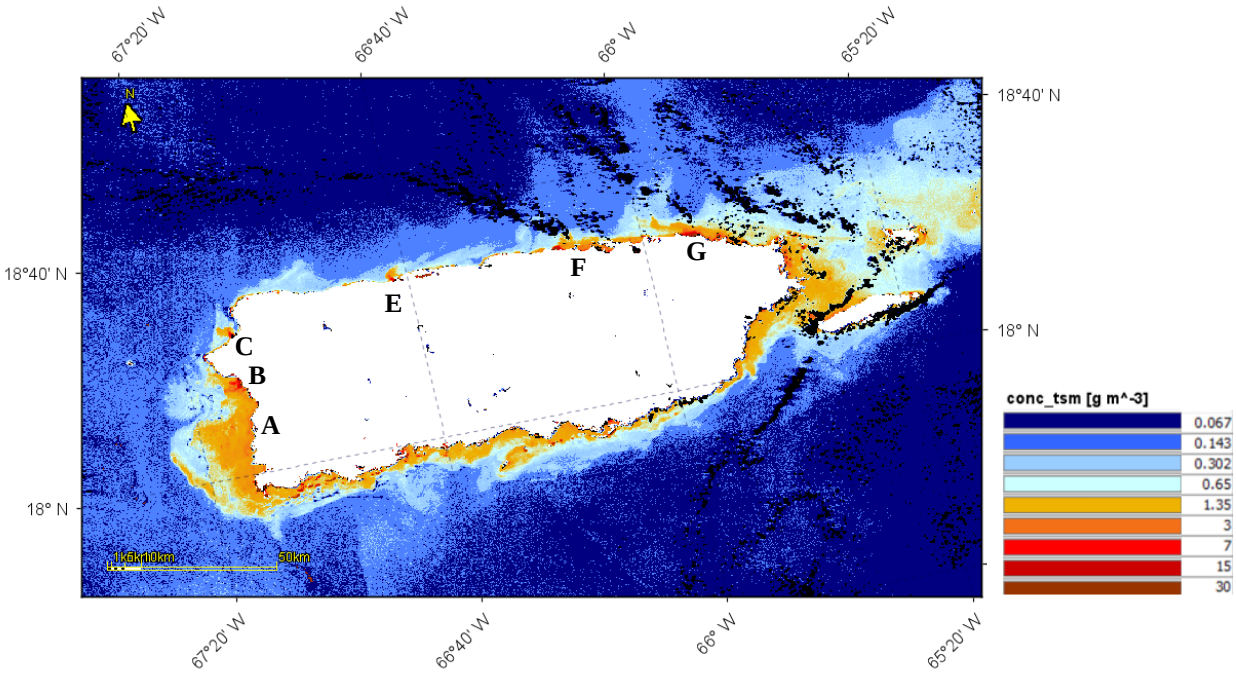

Figure 9: Total Suspended Matter (TSM) concentration retrieved from Sentinel-3 OLCI on September 18, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

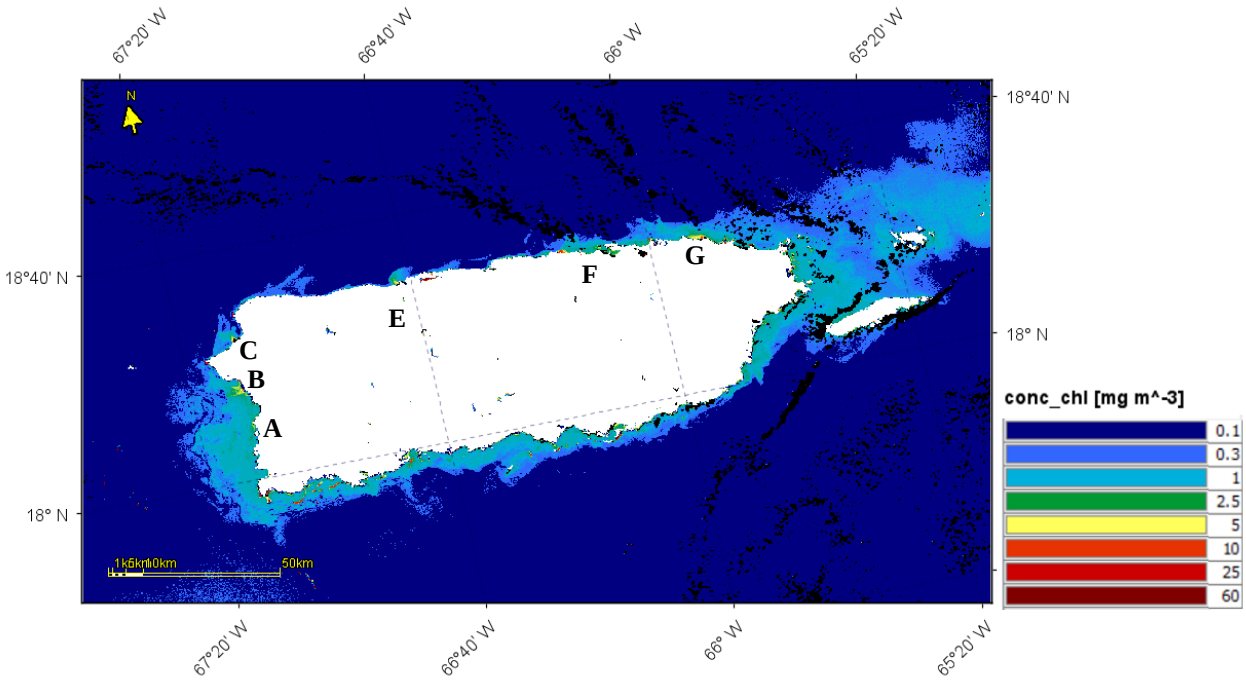

Figure 10: Chlorophyll-a (Chl) retrieved from Sentinel-3 OLCI on September 18, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

After Hurricane Maria *(September 29, 2017)*

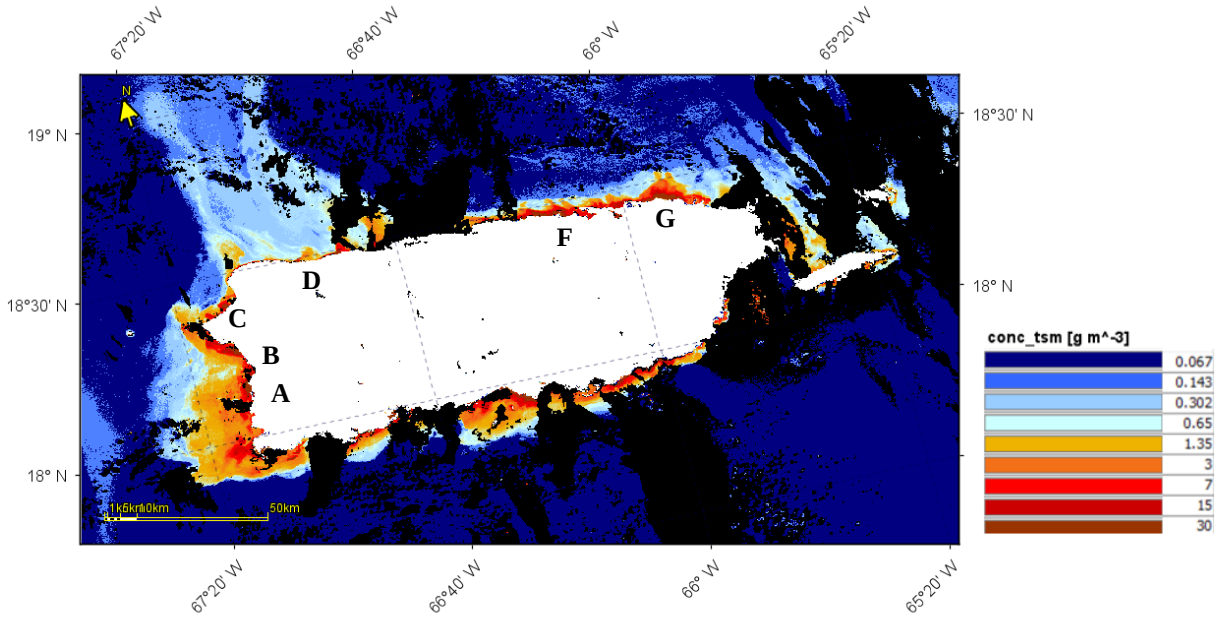

Figure 11: Total Suspended Matter (TSM) concentration retrieved from Sentinel-3 OLCI on September 29, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (D) Río Grande de Arecibo, (F) Río de la Plata, (G) Río Grande de Loíza.*

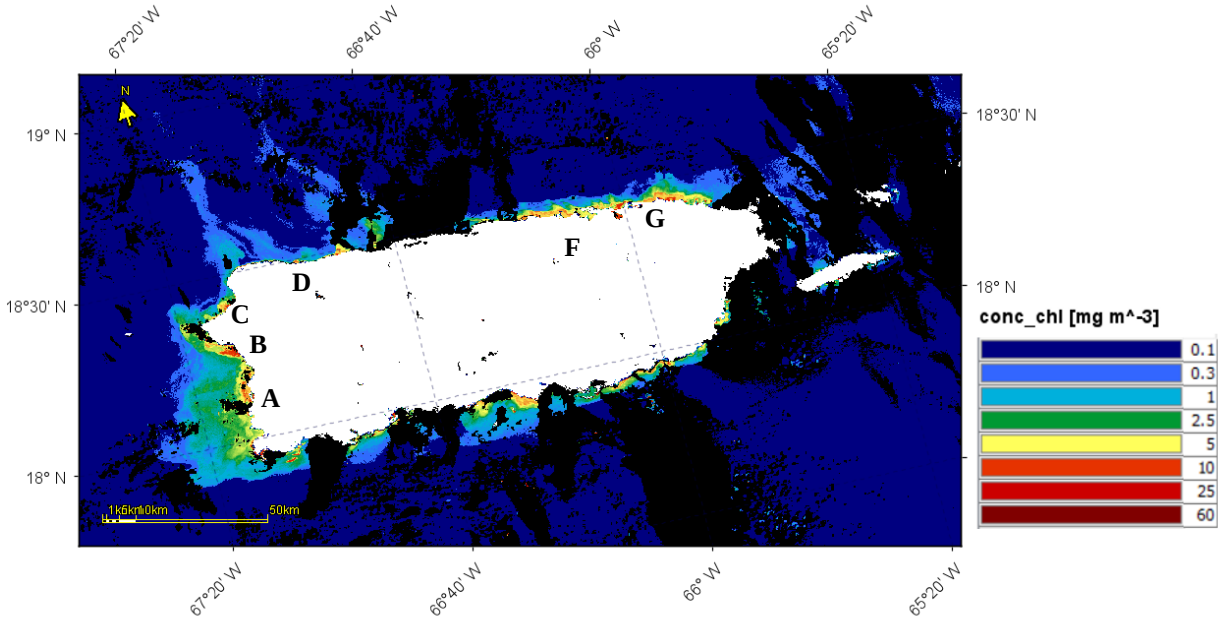

Figure 12: Chlorophyll-a (Chl) retrieved from Sentinel-3 OLCI on September 29, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (D) Río Grande de Arecibo, (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

After Hurricane Maria *(October 4, 2017)*

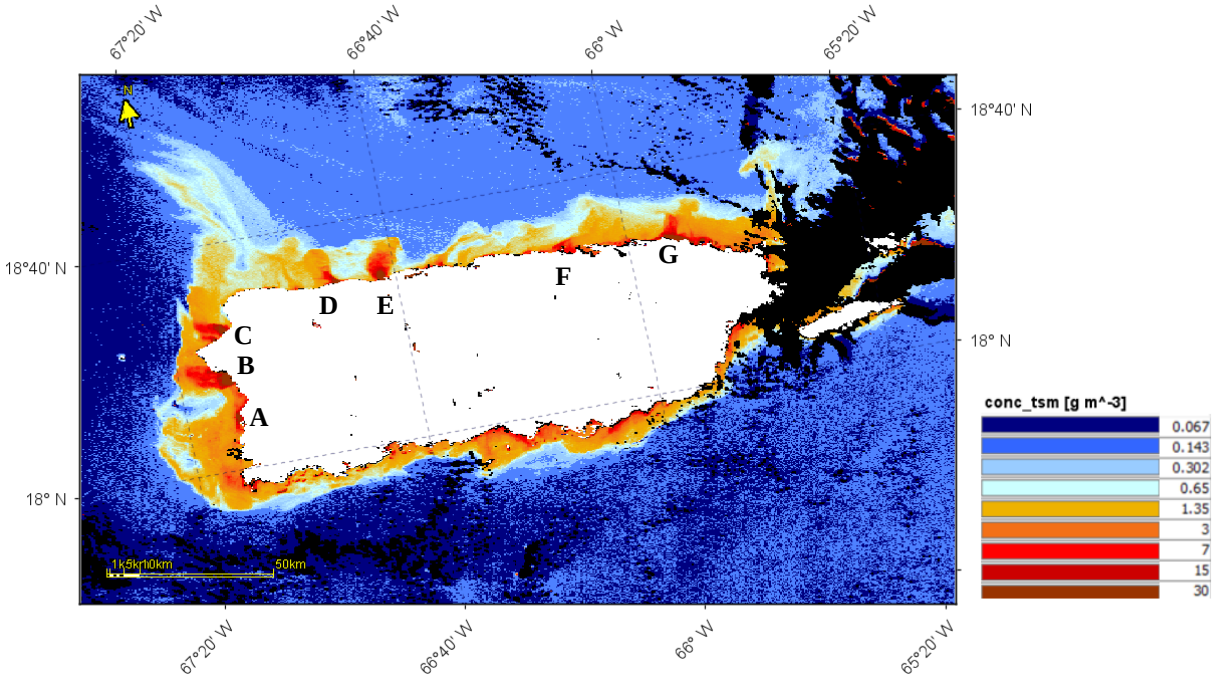

Figure 13: Total Suspended Matter (TSM) concentration retrieved from Sentinel-3 OLCI on October 4, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (D) Río Grande de Arecibo, (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

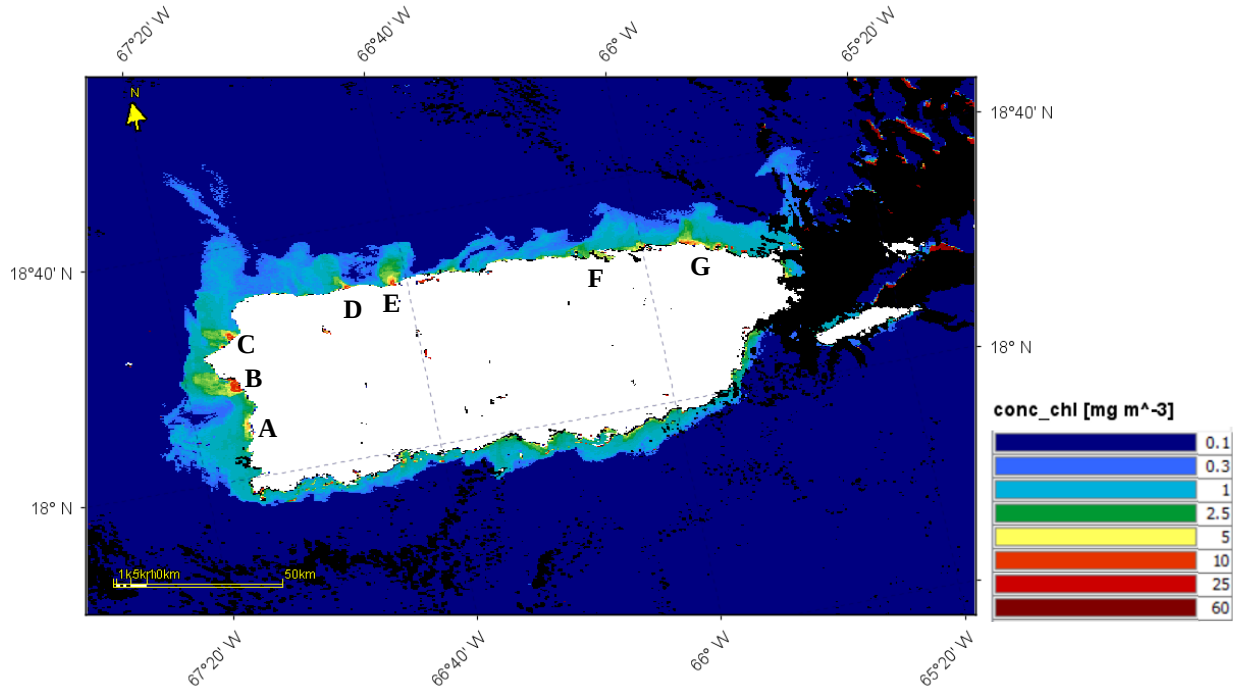

Figure 14: Chlorophyll-a (Chl) retrieved from Sentinel-3 OLCI on October 4, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (D) Río Grande de Arecibo, (E) Río Grande de Manatí (F) Río de la Plata, (G) Río Grande de Loíza.*

After Hurricane Maria *(October 7, 2017)*

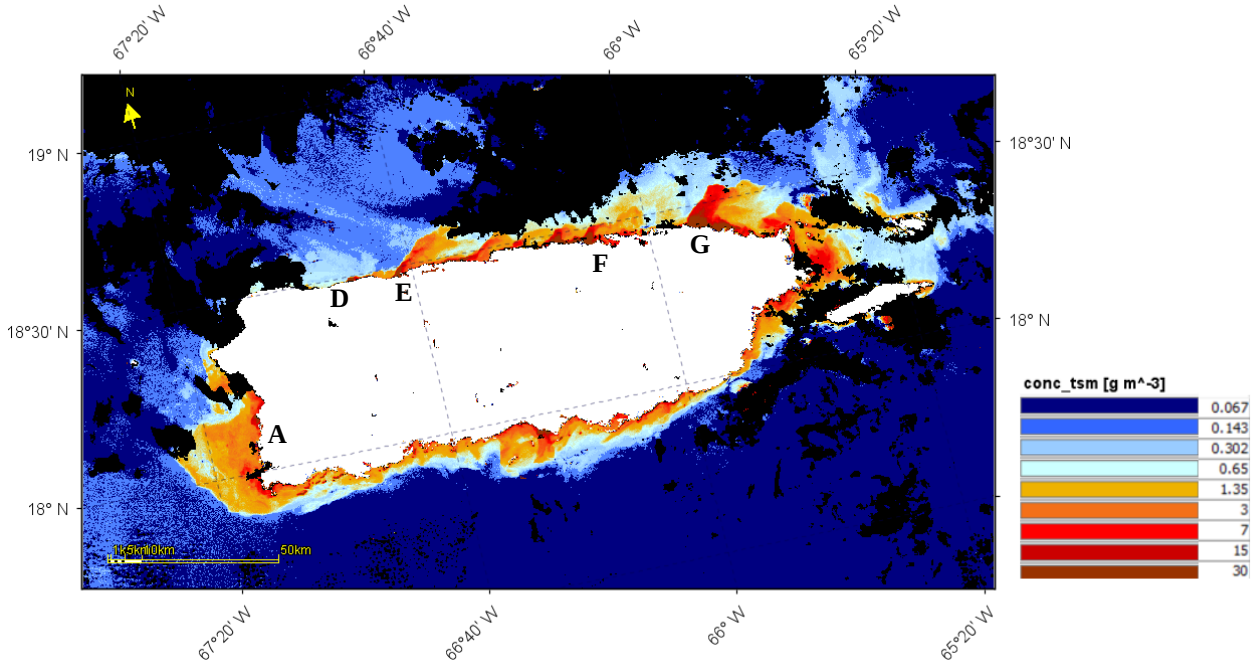

Figure 15: Total Suspended Matter (TSM) concentration retrieved from Sentinel-3 OLCI on October 7, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (D) Río Grande de Loíza (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

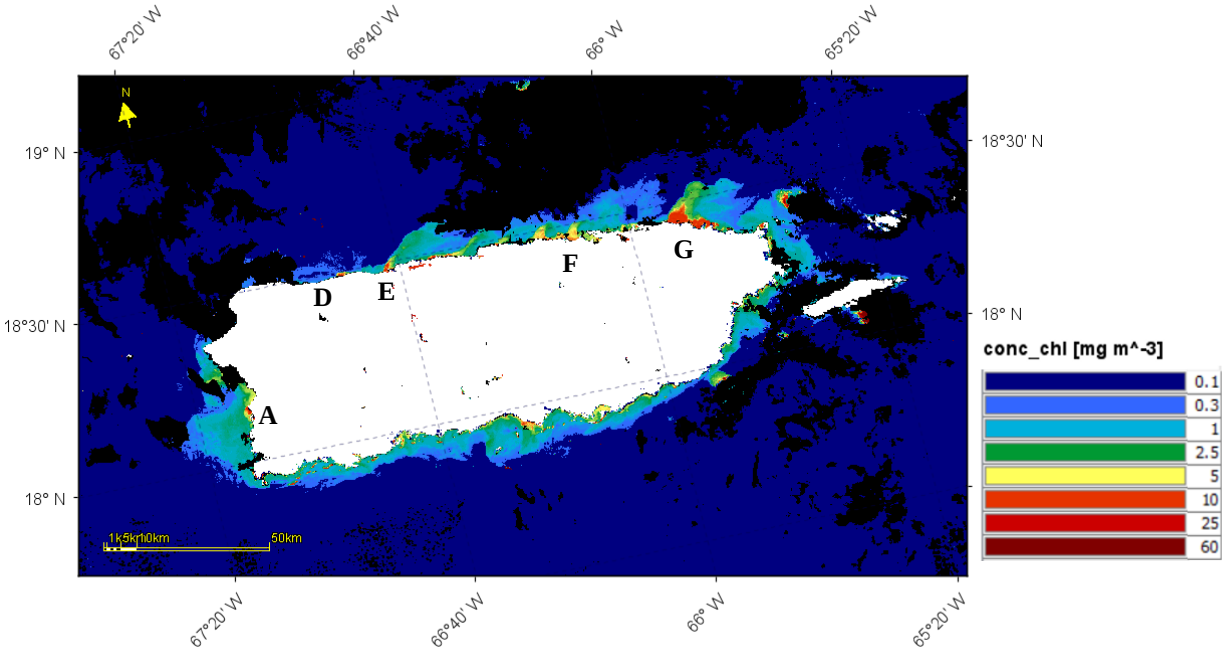

Figure 16: Chlorophyll-a (Chl) retrieved from Sentinel-3 OLCI on October 7, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(A) Río Guanajibo, (D) Río Grande de Loíza (E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

After Hurricane Maria *(October 11, 2017)*

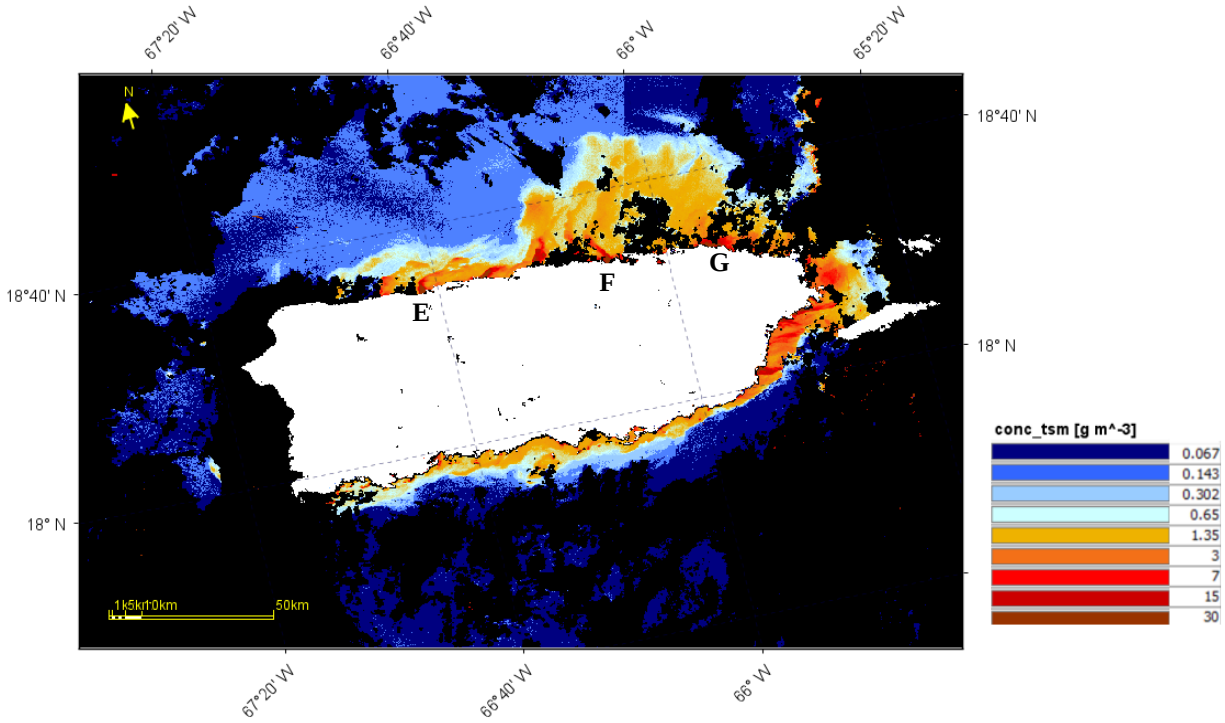

Figure 17: Total Suspended Matter (TSM) concentration retrieved from Sentinel-3 OLCI on October 11, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

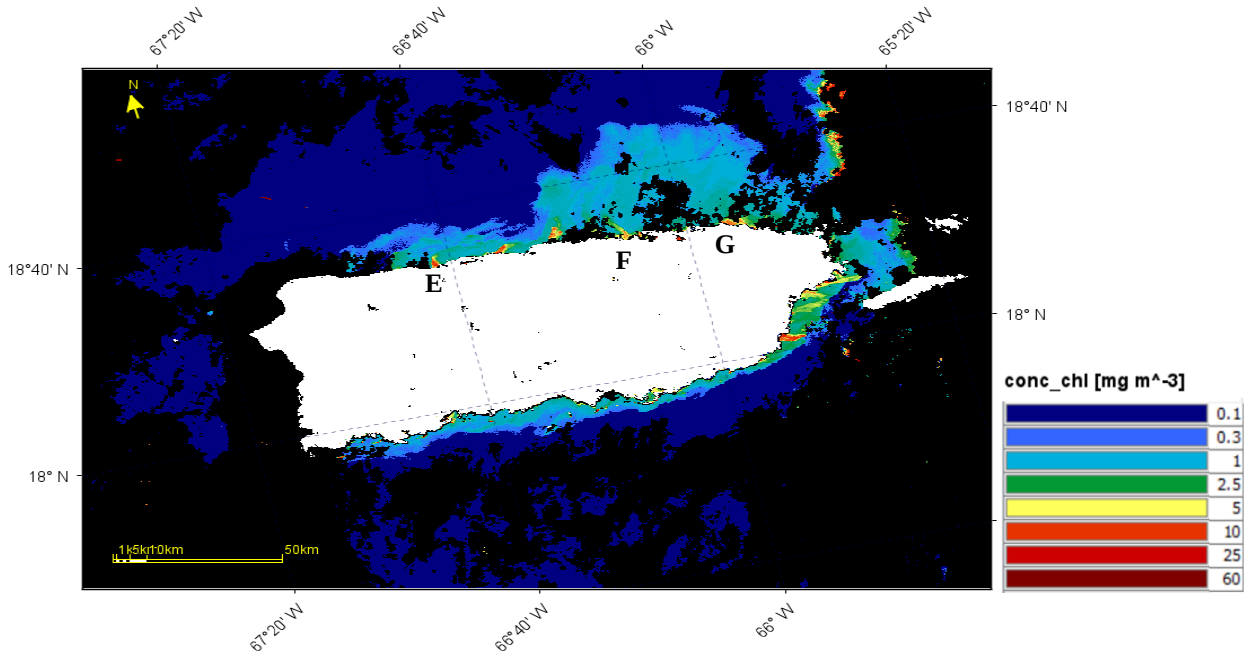

Figure 18: Chlorophyll-a (Chl) retrieved from Sentinel-3 OLCI on October 11, 2017. The area in black indicates the clouds present. Discharge from some rivers: *(E) Río Grande de Manatí, (F) Río de la Plata, (G) Río Grande de Loíza.*

Discussion

The level-2 products generated by the C2RCC processor showed the total suspended matter (TSM) concentration and chlorophyll-*a* (Chl-a) before and after Hurricane Maria.

Figure 9 and 10, showed values of TSM concentrations less than $7\ g/m^3$ and Chl-a less than $10\ mg/m^3$around Puerto Rico before Hurricane Maria.

On the contrary, chlorophyll-a values increased after Hurricane María (Figure 14) especially in river discharges for: (A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río de Culebrinas, (D) Río Grande de Arecibo, (F) Río de la Plata, and (G) Río Grande de Loíza. The increase concentrations of chlorophyll-a reflect an increased in phytoplankton. The increase in phytoplankton is assumed to be the result of high discharge of nutrient-rich river water (Warne et al., 2006).

In addition, the total suspended matter (TSM) concentrations after Hurricane Maria increased around $30\ g/m^3$ near river discharge (Figure 4,7,17). As the sediment moves away from the coast its concentrations decrease approximately $0.143\ g/m^3$ (Figure 4,7,17).

The total suspended matter (TSM) concentrations and chlorophyll-*a* (Chl-a) may take months until they are reduced. For example, concentrations of phytoplankton will decrease as those concentrations become diluted and as nutrients from rivers are consumed.

Conclusion

In general, this work recovered concentrations of chlorophyll-a (Chl-a) and total suspended matter (TSM) using the Case-2 Regional CoastColour algorithm (C2RCC). The hypothesis was accepted because values showed low concentrations of SST and Chl-a in rivers before Hurricane Maria (extreme rain event). On the contrary, values showed a higher concentration of total suspended matter (TSM) and chlorophyll-a (Chl-a) after the extreme rain event. Studying these parameters of water quality is important to protect aquatic ecosystems since the amount of sediment in rivers can degrade water quality. In addition, C2RCC algorithm provide a useful evaluation of the effects of Hurricane Maria on the discharge of Puerto Rico's rivers. Future work will consist of products validation with in-situ measurements for new extreme precipitation events. The in-situ data can provide accurate measurements of total suspended matter (TSM) concentrations, chlorophyll-a (Chl-a) and turbidity levels.

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