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SPATIAL AND TEMPORAL ESTIMATION OF TOTAL SUSPENDED SEDIMENTS AFTER LANDSLIDES EVENTS TRIGGERED BY HURRICANE MARIA IN PUERTO RICO

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1. ABSTRACT

Recent studies in Puerto Rico have monitored the effects of mass movement in response to natural factors associated with tropical atmospheric events, which imperatives the necessity to watch rivers and streams' channels on the island. Suspended sediments are vital for carrying nutrients to aquatic organisms through watersheds and nearby waterbodies. However, their increases upstream represent water quality degradation as they function as a fluid waterway travel for pollutants. This study seeks to validate the influence of eroded materials from the mountainous range of Puerto Rico by quantifying the total of suspended sediments (TSS) in coastal marine waters using satellite imagery. We expect to determine a relationship between the occurrence of landslides and the TSS. The timeline follows a series of short-term periods, placed as: **[a]** ***before*** the passages of Hurricanes Irma and Maria, **[b]** ***during*** the month of both hurricanes over Puerto Rico, and **[c]** ***after*** these events. As a result, we found that the higher values of TSS are noticed from the river mouth to roughly two kilometers into the Atlantic Ocean.

Keywords: suspended sediments, landslides, watersheds, SENTINEL-3, Puerto Rico

2. INTRODUCTION

Watersheds serve as storage for sediment residue and, depending on their mechanisms to transport deposits, are described as active, inactive, or semi-active (Larsen, 2012). A fundamental aspect of studying hydrological phenomena is measuring sediment flow patterns through watersheds due to their relevance in the environmental processes and fluvial transport (Larsen, 2012; Pereira et al., 2019; Zeng et al., 2022). The concentration of suspended sediments is a crucial indicator for sampling water quality, monitoring pollutants, and understanding geomorphological processes in urban and suburban settings (Gellis et al., 2016; Zeng et al., 2022). In Puerto Rico, the increase in upstream sediments threatens drinking water sources and water bodies on the coast

(Yuan et al., 2015). Emphasizing watershed management plans help in defining sources of contamination, reducing events of erosion, and improving mitigation actions (San Juan Bay Estuary Program, 2020).

2.1 Purpose and Scope

The proposed study seeks to evaluate the discharge of total suspended sediments at the river mouth with the occurrence of landslides in the river basin. In Puerto Rico, suspended sediment concentration varies in response to natural factors, including mass movement (Gellis, 2013). As a result, runoff events serve as a mechanism for transporting eroded materials downstream directly to coastal waters (Larsen, 2012). This study aims to analyze if mass wasting events in upper lands impact the discharge of suspended sediments through the watershed and eventually increase their concentration in open ocean waters. This research's primary goal is to better understand the relationship between landslide events and the discharge of total suspended sediments over time. The feasibility of using satellite imagery and Geographic Information Systems to study such a relationship is a key conclusion of this study.

2.2 Background Information

Due to the shortage of river monitoring, lack of sediment routing, and the need for *in-situ* data, remote sensing techniques represent a spatially and comprehensive tool for improving sediment transportation studies (Pereira et al., 2019). Previous studies have demonstrated that remote sensing techniques estimate concentrations of suspended sediments from the light reflected by the water column (Cremon et al., 2019; Kyryliuk and Kratzer, 2019). This study explores the total suspended sediments by evaluating aerial imagery from SENTINEL-3 and focuses on extreme precipitation events that accelerate landslides, e.g., Hurricane Maria in September 2017. The European Space Agency (sentinels.copernicus.eu) shares the following information about

SENTINEL-3: a low Earth-orbit satellite with the mission of measuring the topography of the sea surface and the land surface color, among others.

2.3 Sediment Transport Impacts on Coastal Waters

Stormwater runoff is a primary waterway for sediment transportation, which can form rills and increase sedimentation discharge to open waters (Larsen, 2012; Rhea, 2022). Over time provokes sunlight obstruction, reducing photosynthesis and limiting oxygen absorption of aquatic organisms (Gellis and Brakebill, 2017; Rhea, 2022). In addition to being reported as a degrading phenomenon in coral reef habitats in Puerto Rico (Gellis, 2013). Reducing sediment discharge and minimizing pollution in coastal waters are critical to conserving estuarine reservoirs (Yuan et al., 2015).

2.4 Hurricanes Irma and Maria and Landslides in Puerto Rico

Sediments in Puerto Rico are attached to agricultural activities, urban growth, and erosion events (Yuan et al., 2015). These factors combined over time have perturbed many already unstable hillsides (Hughes and Schulz, 2020). Extreme weather events commonly trigger landslide occurrences (Larsen, 2012; Hughes and Schulz, 2020). Even though mass wasting events are essential for delivering sediments to lowlands' fluvial systems, many landslides represent a risk for lives and infrastructure in some settings (West et al., 2021; Webb et al., 2022). Understanding how previous storms impacted sediment supplies allows for identifying locations predisposed to soil failures that future-generated tropical disturbances may influence (Gellis, 2013; Gellis and Brakebill, 2017). Also, it helps to define mitigation measures, prevent risk, and lower economic losses (West et al., 2021; Vergara et al., 2022).

Puerto Rico experiences a susceptibility to downward movements of soil, rocks, and vegetation (Hughes and Morales-Vélez, 2020; Hughes and Schulz, 2020; West et al., 2021). Most landslides, which include rock falls, debris flow, and other slope failures, generate significant impacts associated with the destruction of accessibility to roads, bridges, and private properties (Hughes and Schulz, 2020; Vergara et al., 2022). Hurricane Maria's winds and high-intensity rainfall increased soil saturation, accelerated weathering, and caused the highest density of mass wasting reported in the mountainous interior of Puerto Rico's central range (Irizarry-Brugman et al., 2021). Recent research by Hughes and Schulz (2020) completed a digital landslide inventory and identified that more than 70 thousand landslides through the island of Puerto Rico were triggered after Hurricanes Irma and Maria in September 2017 (Hughes and Morales-Vélez, 2020).

3. METHODS

3.1 Geographical Setting

Puerto Rico is the smallest island-archipelago of the Greater Antilles in the Caribbean and has predominant mountain landscapes (Gellis, 2013; Hughes and Schulz, 2020). The island experiences seismic activity due to its location on the Caribbean plate and, because of its geographic situation, is exposed to tropical weather systems (Hughes and Morales-Vélez, 2020). As a result, Puerto Rico is highly susceptible to weathering and slope failures (Irizarry-Brugman et al., 2021). In addition, these influence the runoff, which carries eroded materials downstream directly to coastal waters (Larsen, 2012). This study considered the watersheds that included the municipalities with the higher density of landslides per square kilometer. These occurrences were identified by Hughes et al. (2019), *see **Figure 1***. The highest number of landslide occurrences (>100) per square kilometer were observed in the municipalities of Maricao (west-central) and Utuado (central), *see **Figure 2***. Therefore, this study considers two (2) watersheds: Añasco (western) and Arecibo (central-western), *see **Figure 3***. The river sources for both watersheds originate along Puerto Rico's Mountain range, central Puerto Rico.

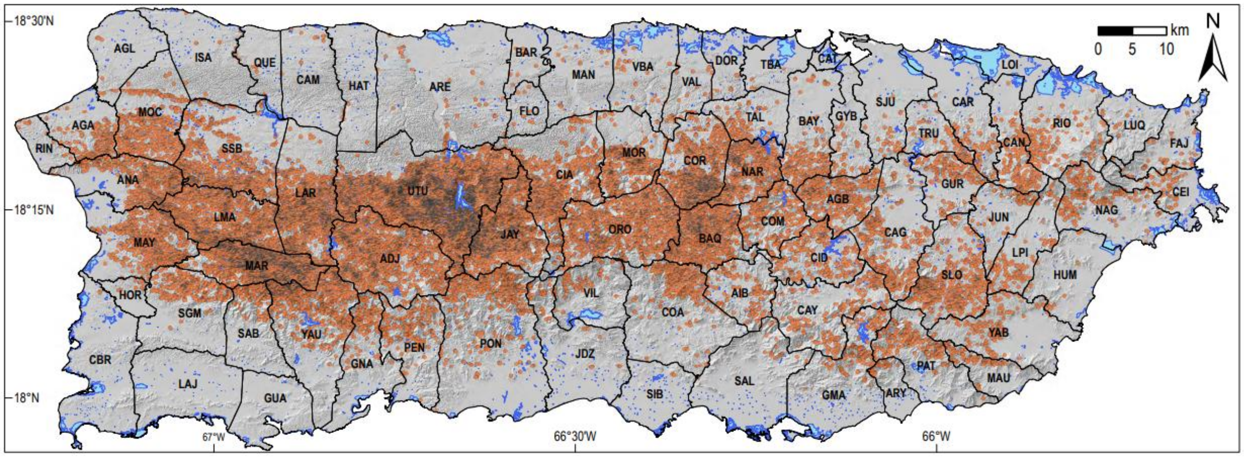


Figure 1. Landslides inventory map after Hurricane Maria in September 2017. *This map represents the inventory of 71,431 slope failures triggered by Hurricane Maria in Puerto Rico. According to Hughes and Schulz (2020), each landslide is represented by a small circle (orange) and were identified using geo-referenced aerial and satellite imagery.*

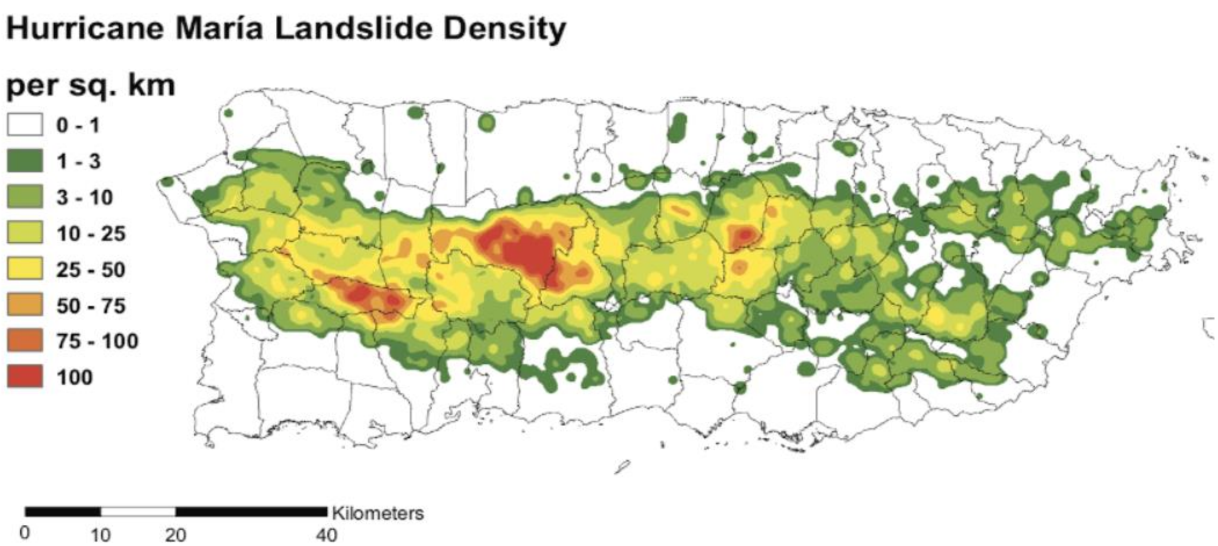


Figure 2. Landslide density map per square kilometer in Puerto Rico after Hurricane Maria in September 2017. *Hugues et al. (2019) identified landslide events in 72 municipalities (out of 78 total). The highest number of landslide occurrences (>100, red color) per square kilometer was in municipalities located in the Mountain range (central Puerto Rico).*

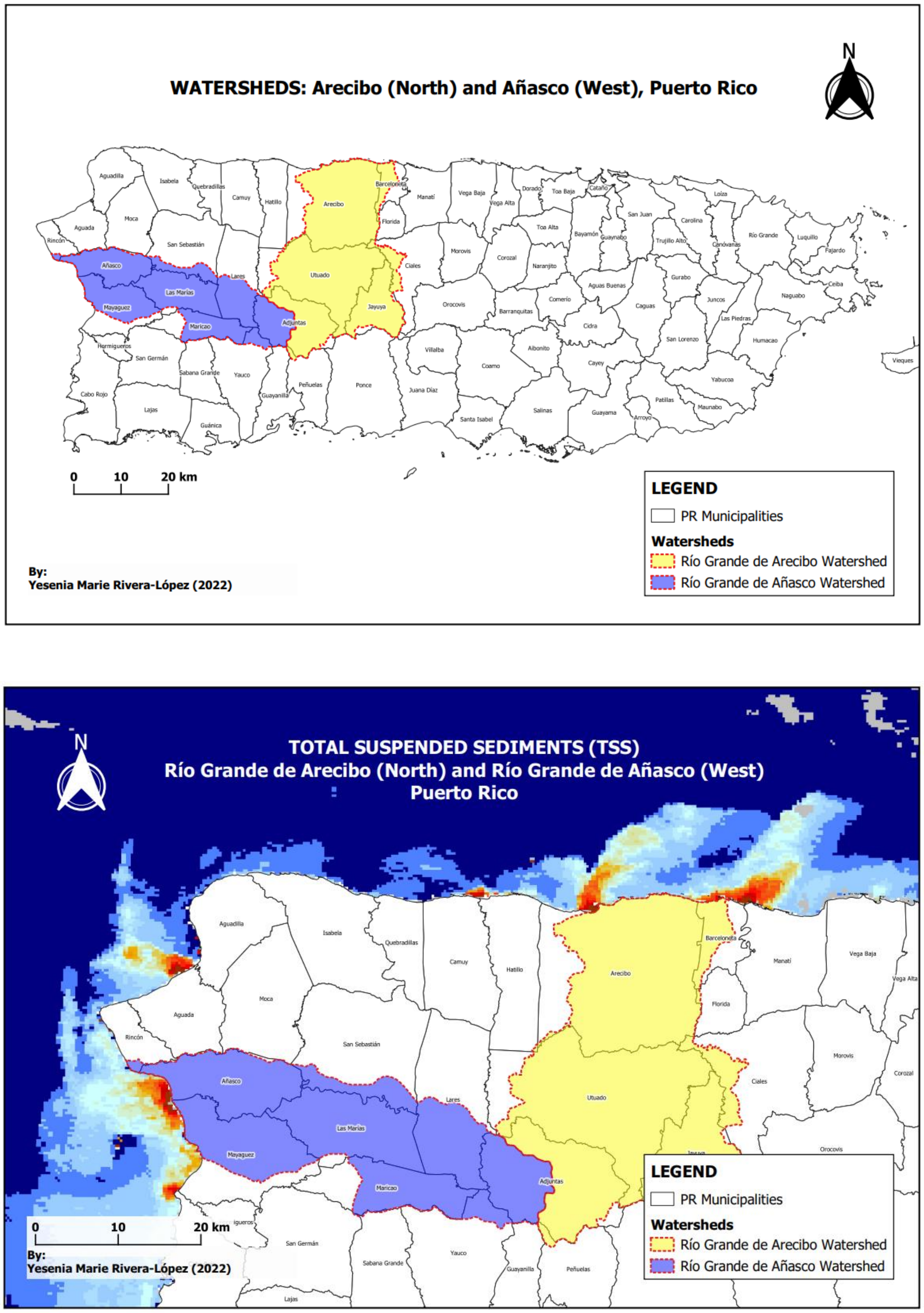


Figure 3. A map of Puerto Rico with the 78 municipalities and two watersheds. *This study will focus on the river mouths of Río Grande de Arecibo (yellow) and Río Grande de Añasco (blue). These watersheds were reported with the highest density of landslides, with over 30 landslides per square kilometer (Hughes et al., 2019).*

3.2.1 Añasco Watershed

Río Grande de Añasco is located in the western section of Puerto Rico in the Añasco municipality, and it roughly delimitates 122,700 acres (DRNA, 2017; National Water Quality Monitoring Council, 2022), *see **Figure 4***. According to the USGS (2022), the drainage area is equal to 139 square-mile (sq. mi). The Río Grande de Añasco flows west from the Mountain range and discharges into the Bahía de Añasco. The hydrological basin of the Río Grande de Añasco lies in an alluvium floodplain composed of clay, silt, and sand (USGS, 1996). Predominantly, the watershed is forested, and the landscape is merged with pasture, agricultural activities, and farmlands near the coast (DRNA, 2017).

3.2.2 Arecibo Watershed

The Río Grande de Arecibo watershed is situated in the central-western section of Puerto Rico's north coast with the Atlantic Ocean as a boundary and has about 152,200 acres (USGS, 1996; DRNA, 2017), *see **Figure 5***. The landscape is composed of a transition from agricultural activities in the upper lands to a metropolitan area as it reaches the municipality of Arecibo (DRNA, 2017). In addition, the hydrological basin of the Río Grande de Arecibo lies in an alluvium floodplain, moderately well sorted and composed of quartz, feldspar, and sand grains fragments of plutonic-rocks (Briggs, 1968).

3.2 Satellite Data: SENTINEL-3

Data products from SENTINEL-3 were used to monitor differences in the concentration of suspended sediments. The SENTINEL-3 mission was designed to deliver ocean forecasting and monitoring environmental parameters and climate (Kyryliuk and Kratzer, 2019). To acquire SENTINEL products is necessary to access the Copernicus Open Access Hub (scihub.copernicus.eu, accessed in September 2022).

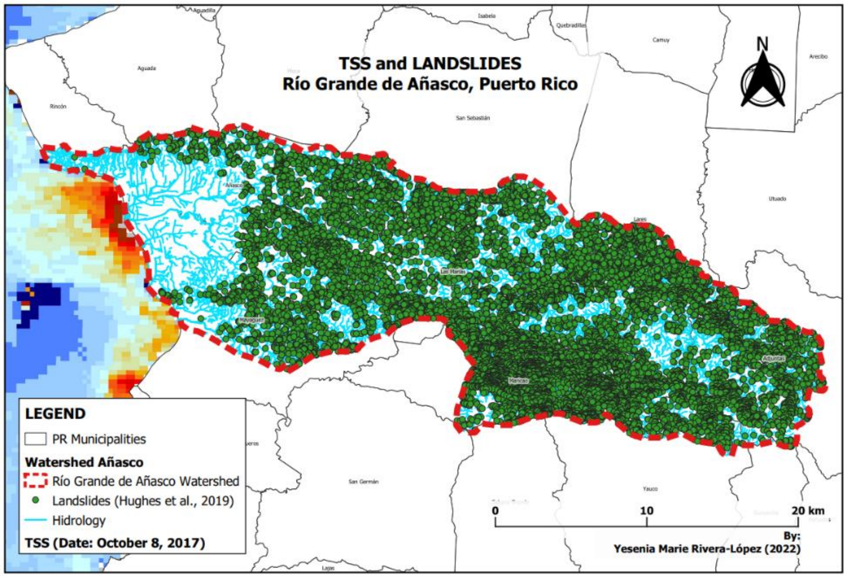


Figure 4.

Río Grande de Añasco watershed. *A small circle (green) represents each landslide within the watershed. This map also includes hydrology (light blue).*

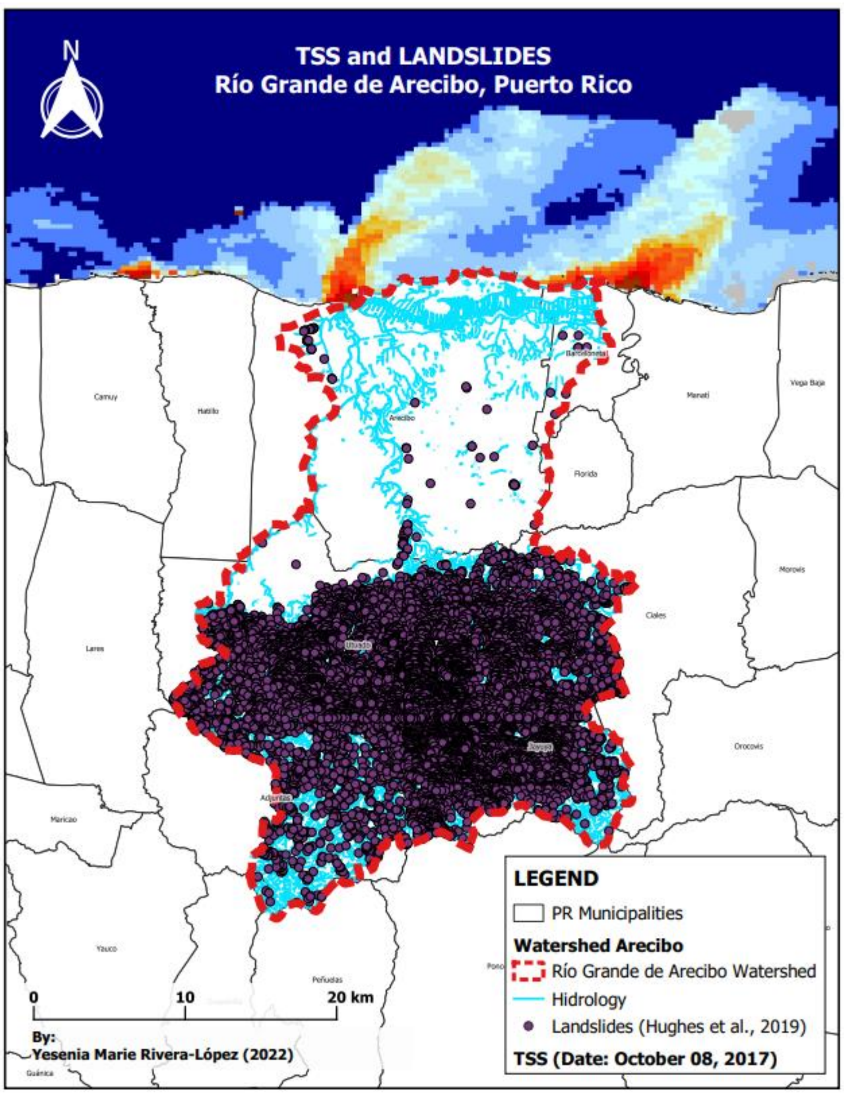


Figure 5.

Río Grande de Arecibo watershed. *The landslide occurrences within the watershed are represented by a small circle (purple). This map also includes hydrology (light blue).*

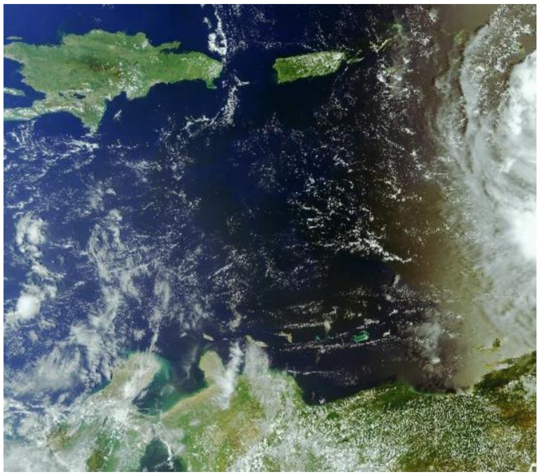
Copernicus Open Access Hub. The Copernicus Open Access Hub is a website developed by the European Space Agency, which provides open and free access to products in the SENTINEL missions.

3.2.1 Selection Criteria

For this study, the selection criteria in the Copernicus Open Access Hub correspond to the mission of SENTINEL-3 and the instrument OLCI. The imagery searches in Copernicus were input from August 2017 to April 2018. Therefore, the data correspond for three (3) periods: **[1]** ***before*** the passages of Hurricanes Irma and Maria, **[2]** ***during*** the month of both hurricanes over Puerto Rico, *see* ***Figure 6***, and **[3]** ***after*** these events. However, only data products without cloud coverage were downloaded for processing and analysis. Each product was downloaded in an OLCI Level-1 data format, which includes atmosphere radiance, radiometric and spectral calibrations (sentinel.esa.int).

Ocean and Land Color Instrument. The Ocean and Land Color Instrument (OLCI) is a push-broom imaging spectrometer with five (5) cameras and 21 spectral bands that collects radiometric measurements at a spatial resolution of 300 meters (sentinels.copernicus.eu).

Aerial Imagery. The aerial imagery download corresponds to August, September, October, November, and December of 2017 and January, March, and April of 2018, respectively; see ***Table 1*** for a summary per month. All the data products downloaded were processed using the SNAP Software.



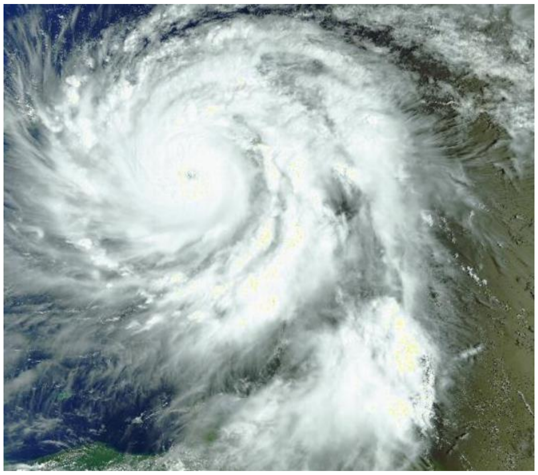


Figure 6. Satellite imagery from SENTINEL-3 obtain at Copernicus (scihub.copernicus.eu). *The first imagery (left) is from September 18, 2017, and the following (right) shows Hurricane Maria on September 19, 2017, a day before it passed over Puerto Rico.*

Table 1. Dates: before, during, and after. *This table summarizes the periods established and shows the dates of each aerial imagery product processed.*

	Period 1 (*before*)	**Period 2 (*during*)**	**Period 3 (*after*)**
MONTH	DD/YYYY	DD/YYYY	DD/YYYY
AUGUST	11/2017 18/2017 22/2017 30/2017		
SEPTEMBER		18/2017	
OCTOBER			08/2017
NOVEMBER			03/2017 23/2017 26/2017 30/2017
DECEMBER			01/2017 04/2017 08/2017 12/2017
JANUARY			23/2018
MARCH			03/2018 07/2018 19/2018 26/2018
APRIL			07/2018 15/2018 30/2018

Sentinel Application Platform (SNAP). The SNAP Software stands for the *Sentinel Application Platform* (earth.esa.int). This application platform contains executable tools for viewing and processing data sensed remotely.

3.2.2 Processing

Each Level-1 product was opened on SNAP for the respective processing. First, a subset was delimited for the island of Puerto Rico. This helps to reduce the processing time when running the OLCI processors. Then, the aerial image is selected for running the Thematic Water Processing using the C2RCC processor. Additionally, a geometric reprojection and cloud mask were applied to each product.

Case-2 Regional CoastColor (C2RCC). The C2RCC processor is software for processing ocean color. This processor is designed for satellite instruments like OLCI and includes atmospheric correction algorithms (Kyryliuk and Kratzer, 2019; RUS, 2020). One of the outputs generated by the C2RCC is concentrations of suspended sediments (Kyryliuk and Kratzer, 2019).

3.2.3 Collecting

For the data collection, a transect was defined, starting at the river mouth to the Atlantic Ocean. The transects include six (6) unique reference points along the river plume, *see **Figure** 7*. Each location represents a specific point of intersection with known latitude and longitude coordinates. In addition, the x-y pixels contain the following: id, date, time, suspended sediments, and chlorophyll concentrations, among others. The information is extracted for each date as a text file (.txt) for the data analysis.

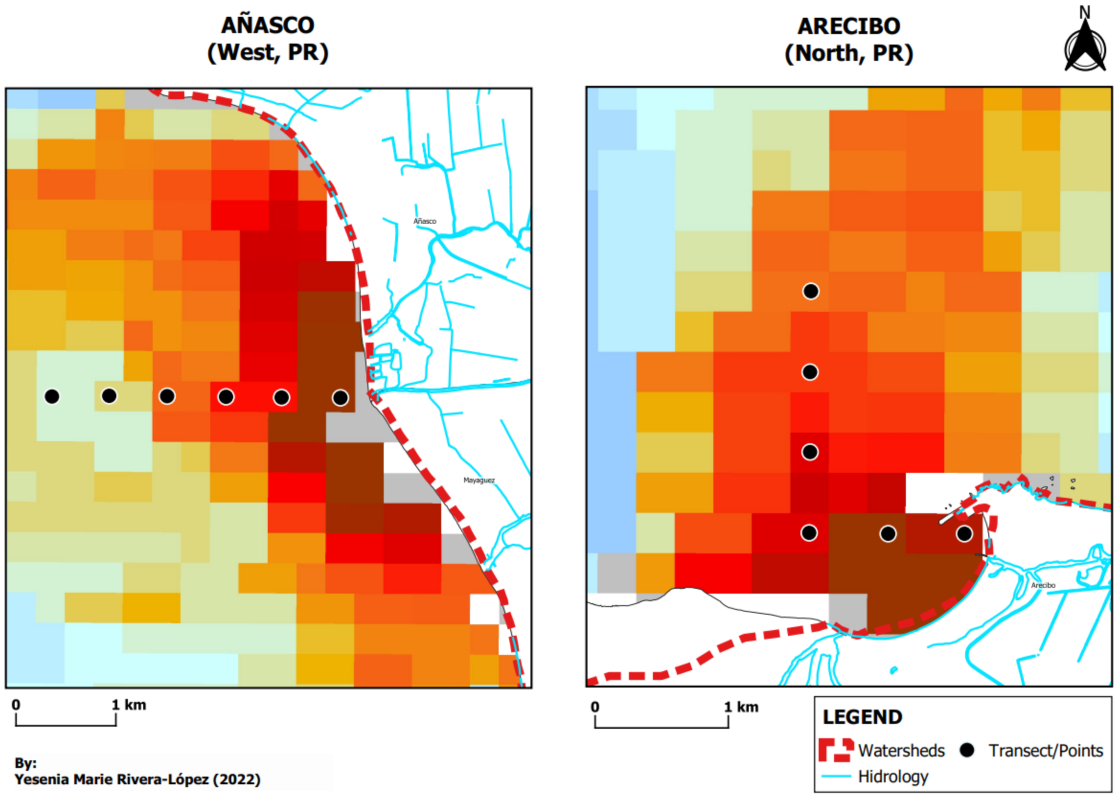


Figure 7. Transects of Añasco and Arecibo. *Each point in the transect is represented by a circle (black). The transects were defined as the flow of the plume, and the distance between points was 0.6 kilometers.*

Transect. The transect was drawn from the river mouth representing 0.0-*kilometers* to the Atlantic Ocean at 3.0-*kilometers*. The distance between reference points is 0.6 kilometers. These were defined as follows:

[a] Point 1 → 0.0 kilometers (from the river mouth)

[b] Point 2 → 0.6 kilometers, *represents: Point 1 + 0.6 kilometers*

[c] Point 3 → 1.2 kilometers, *represents: Point 2 + 0.6 kilometers*

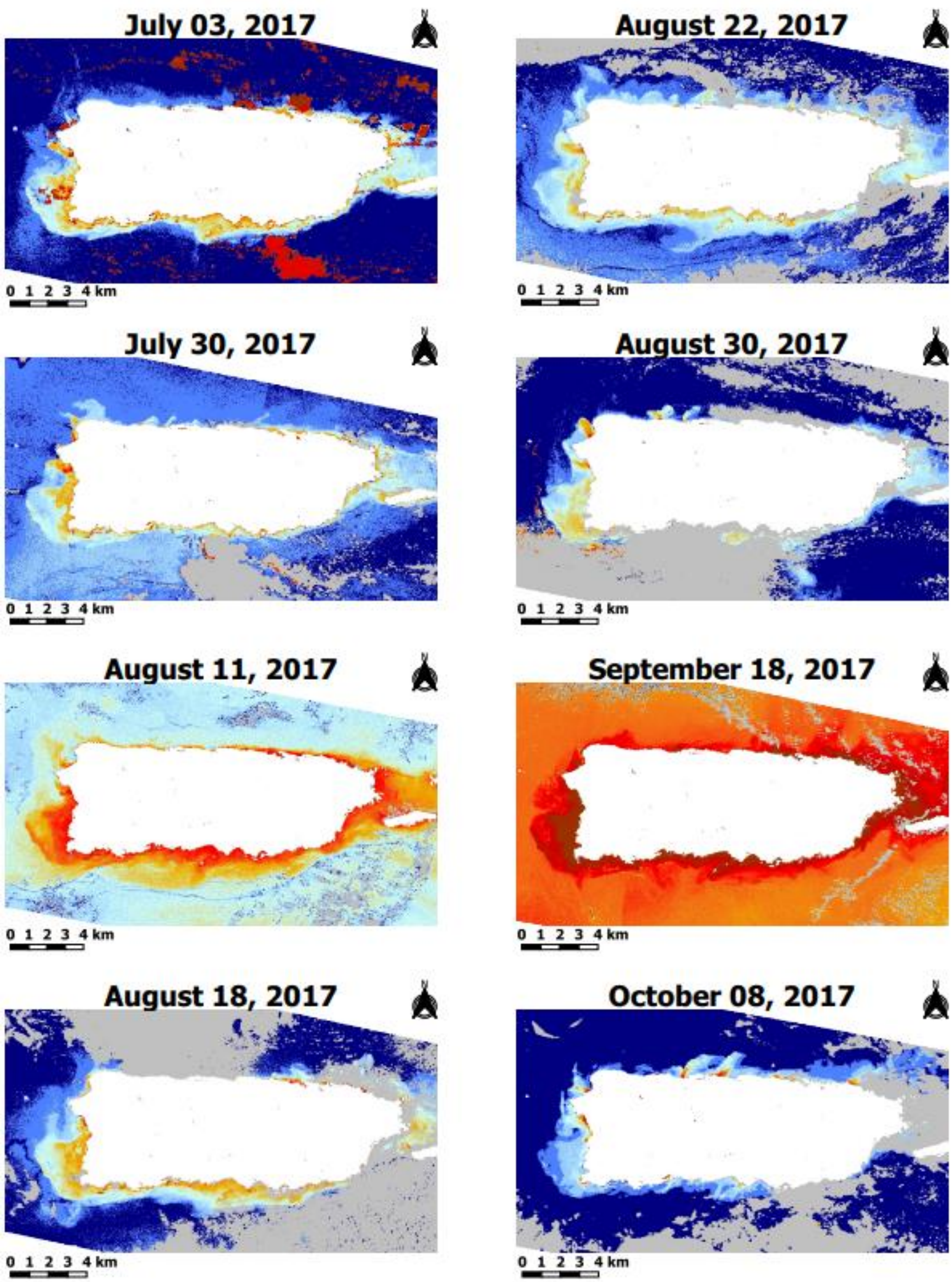
[d] Point 4 → 1.8 kilometers, *represents: Point 3 + 0.6 kilometers*

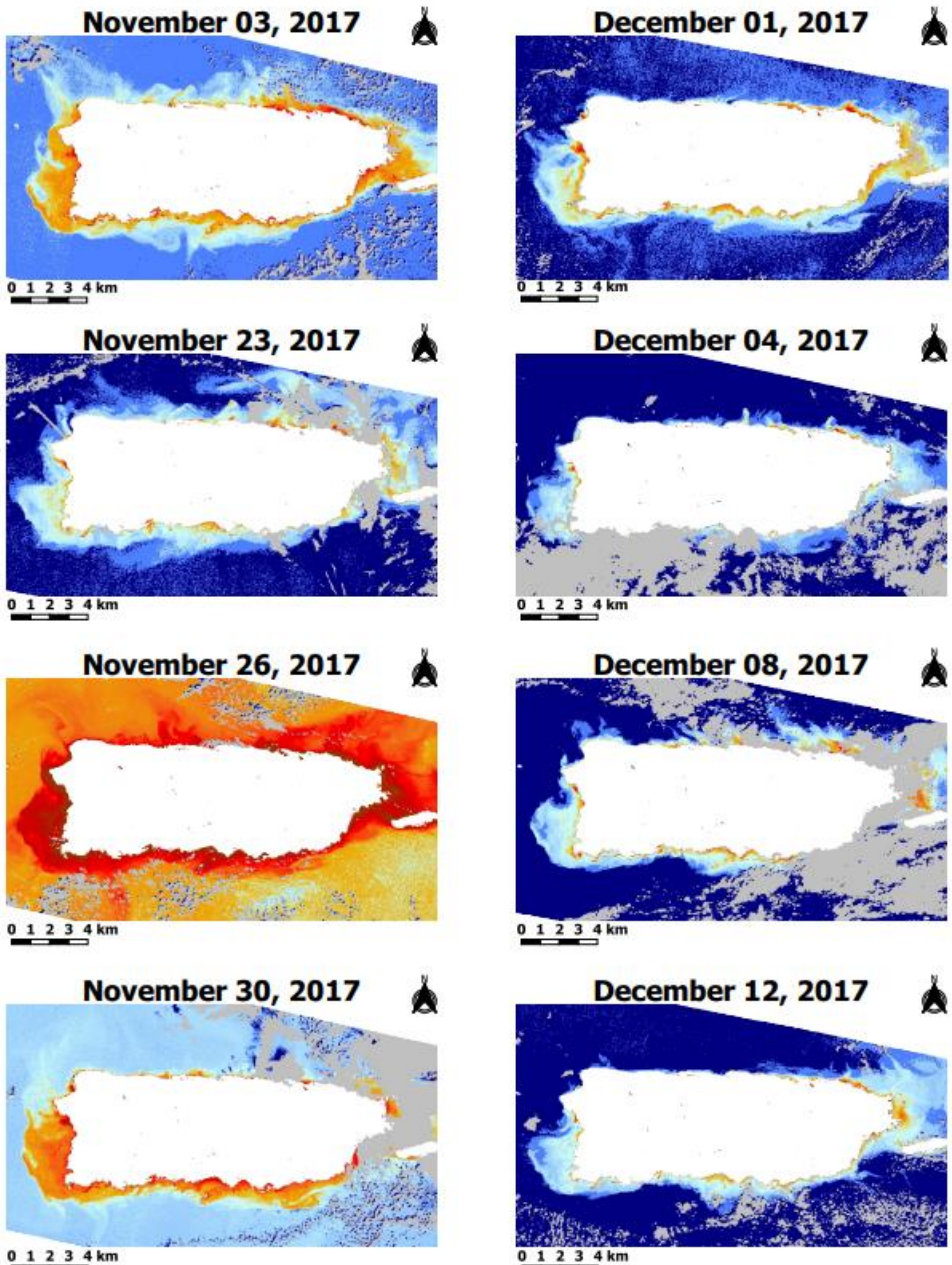
[e] Point 5 → 2.4 kilometers, *represents: Point 4 + 0.6 kilometers*

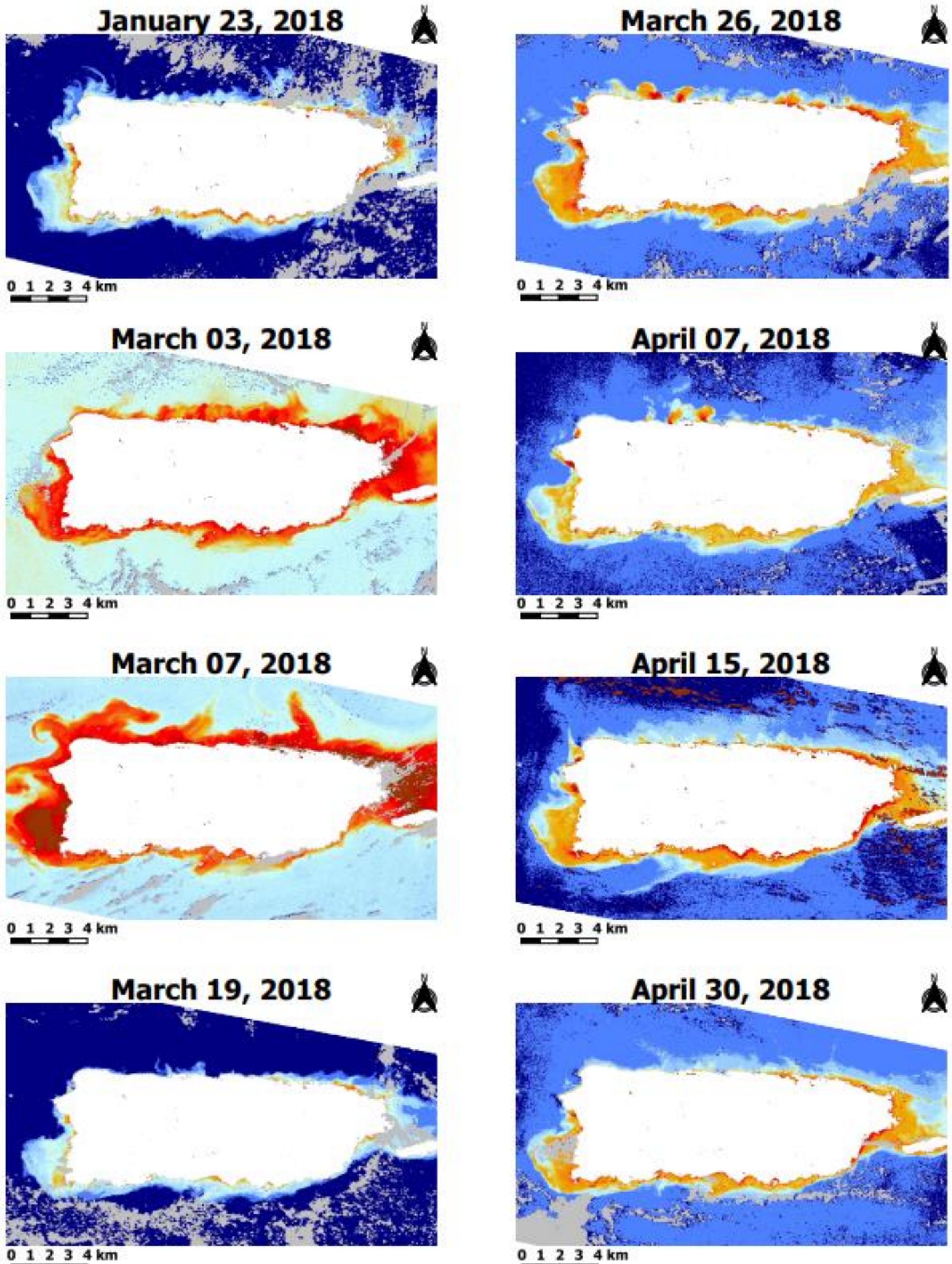
[f] Point 6 → 3.0 kilometers (endpoint on the study), *represents: Point 5 + 0.6 kilometers*

4. RESULTS

4.1 Aerial Imagery

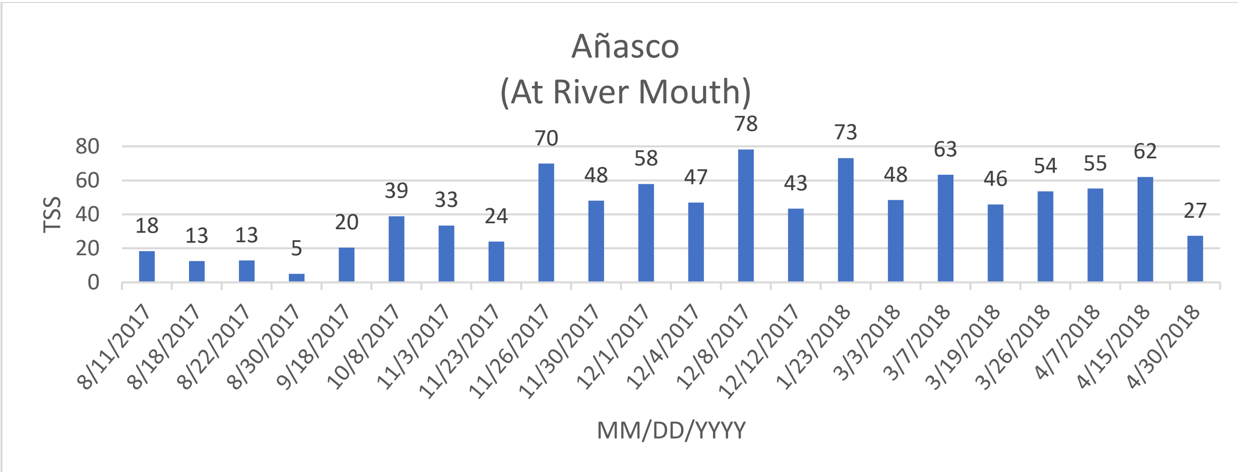


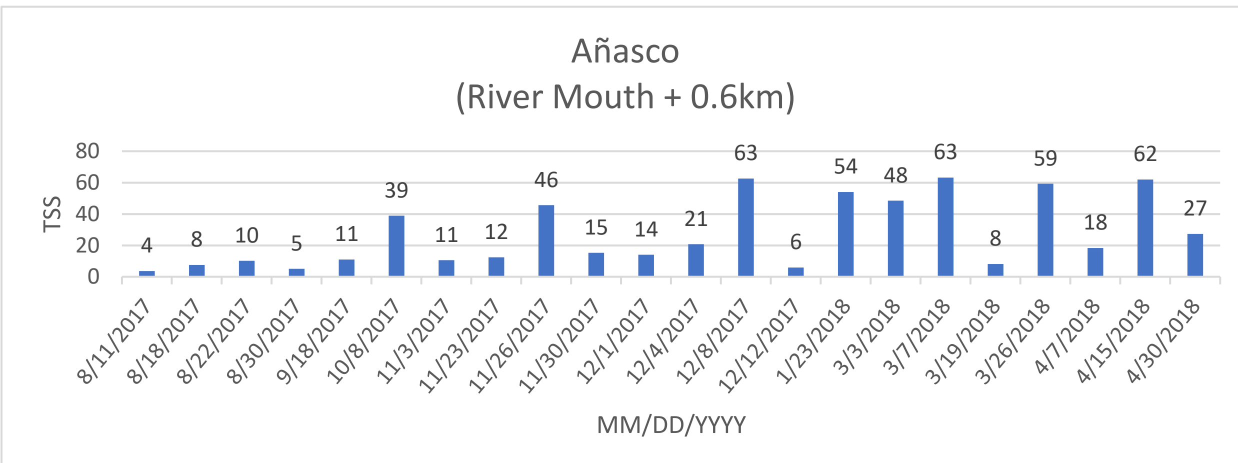

November 03, 2017
0 1 2 3 4 km
December 01, 2017
0 1 2 3 4 km
November 23, 2017
0 1 2 3 4 km
December 04, 2017
0 1 2 3 4 km
November 26, 2017
0 1 2 3 4 km
December 08, 2017
0 1 2 3 4 km
November 30, 2017
0 1 2 3 4 km
December 12, 2017
0 1 2 3 4 km


January 23, 2018
March 26, 2018
March 03, 2018
April 07, 2018
March 07, 2018
April 15, 2018
March 19, 2018
April 30, 2018
0 1 2 3 4 km

4.2 Data Analysis

4.2.1 Añasco Watershed





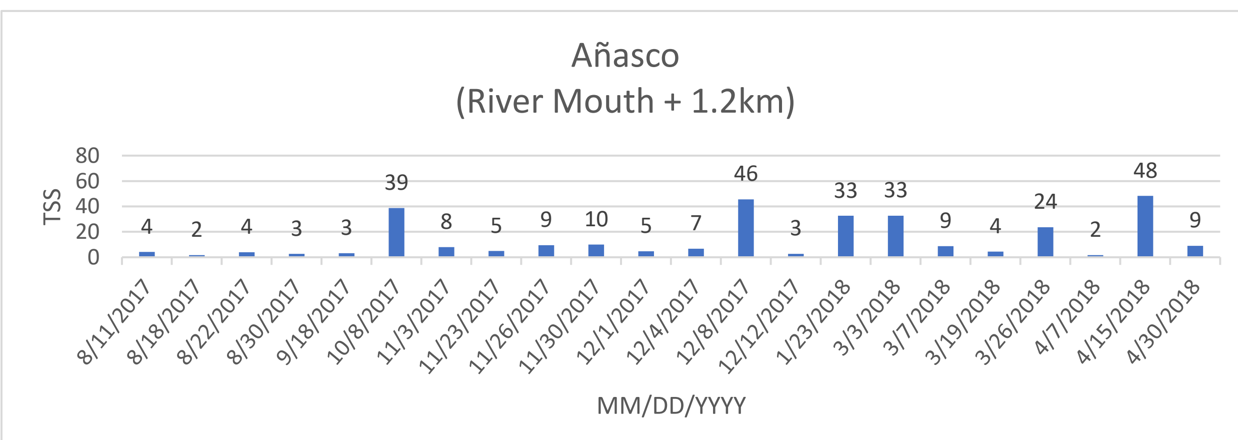
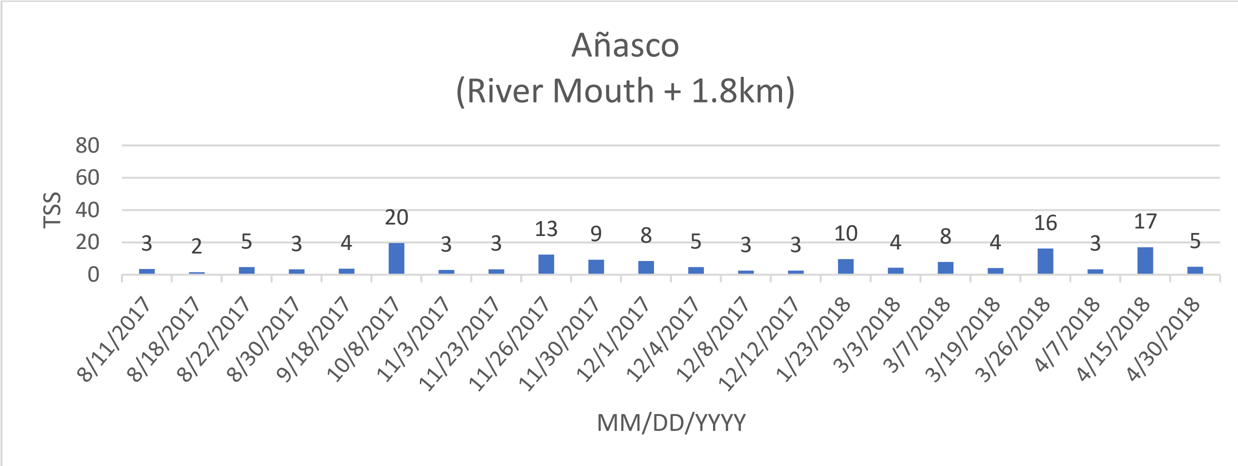
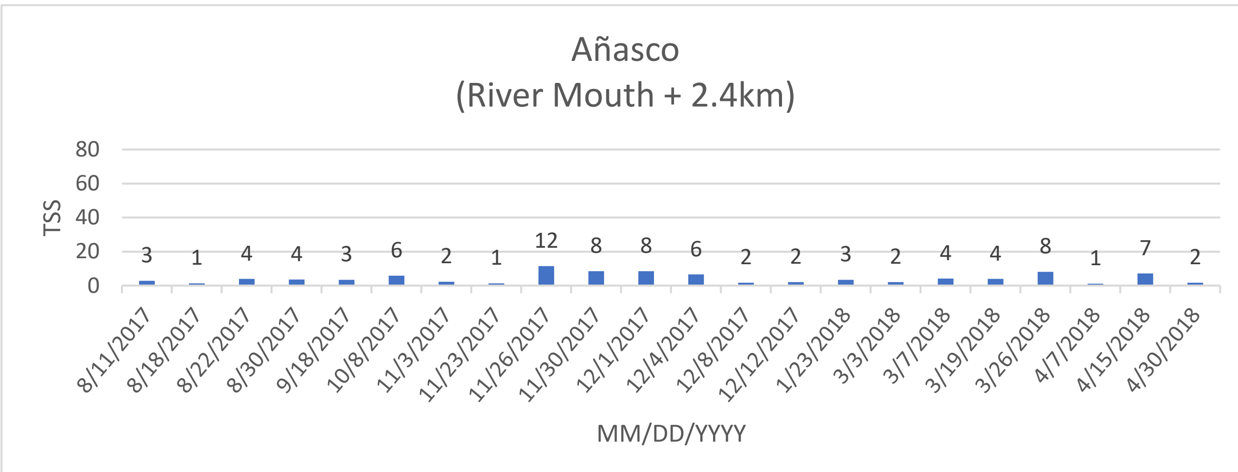


Figure 8. Results of Añasco transect reference points along the river plume (set 1 of 2).





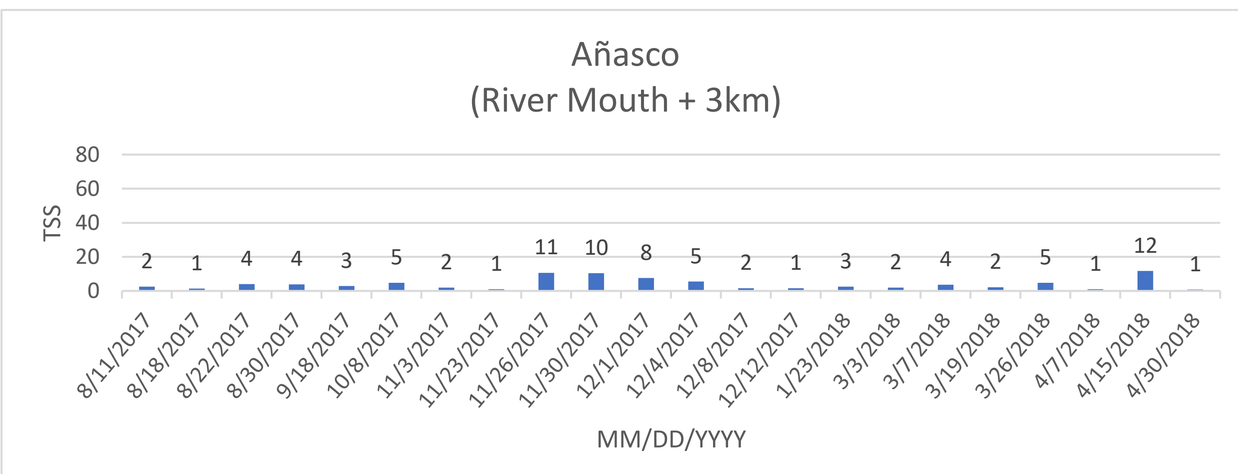


Figure 9. Results of Añasco transect reference points along the river plume (set 2 of 2).

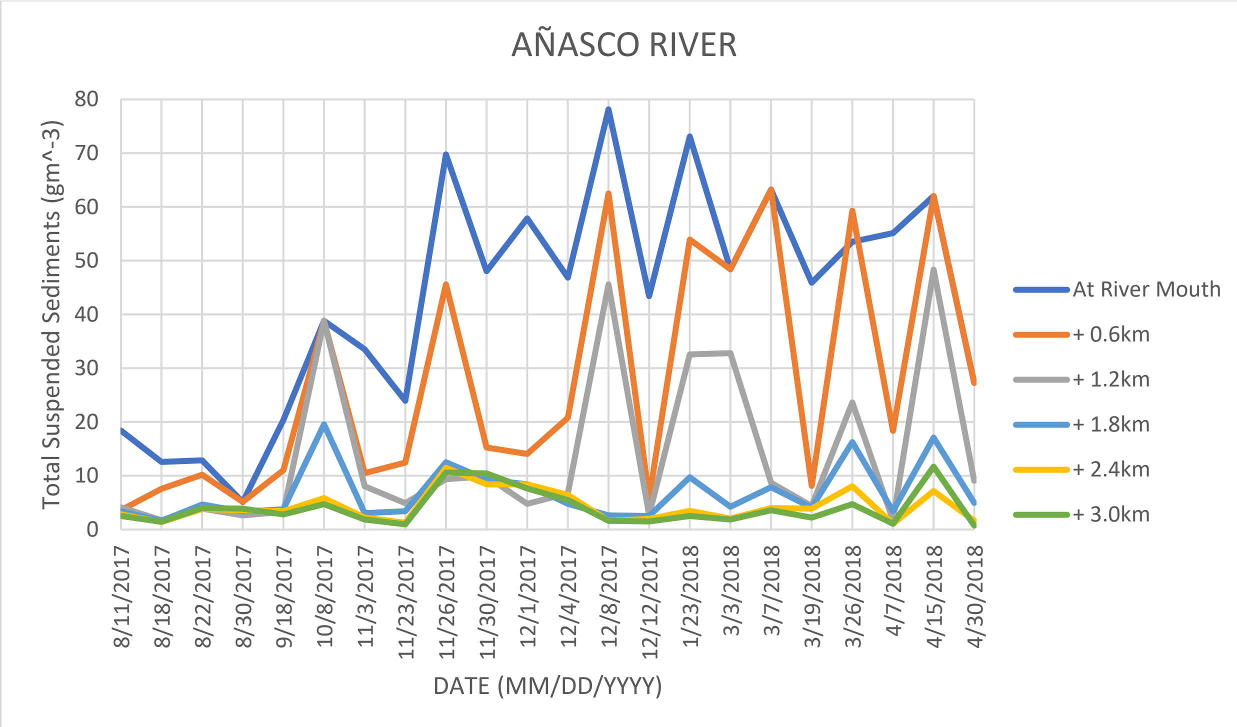


Figure 10. Results of Añasco all reference points along the river plume.

4.2.2 Arecibo Watershed

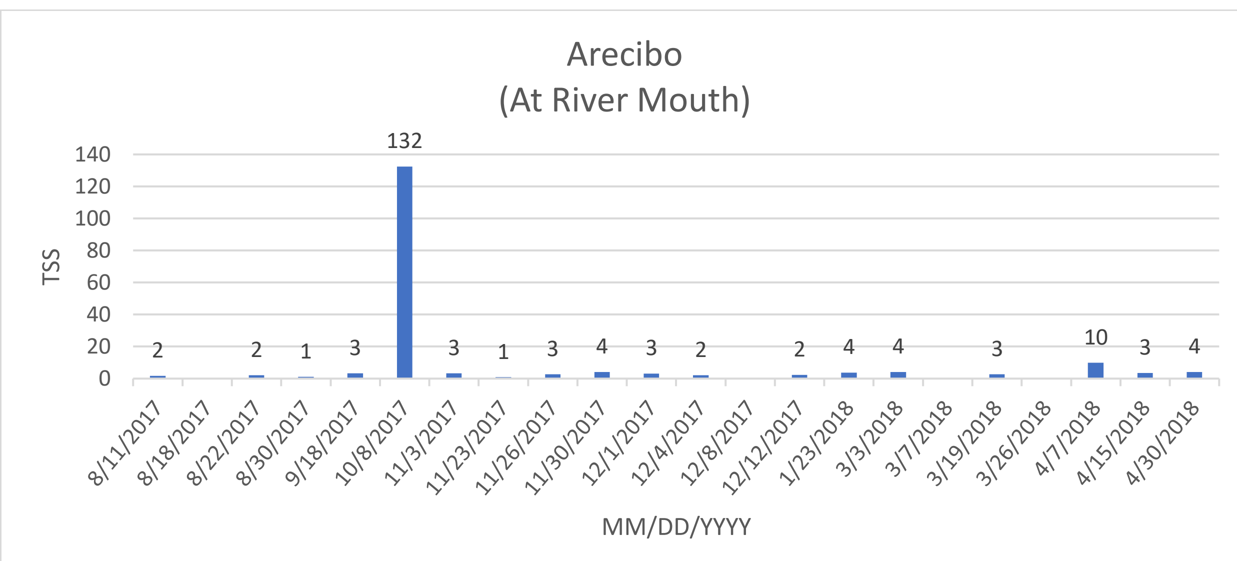
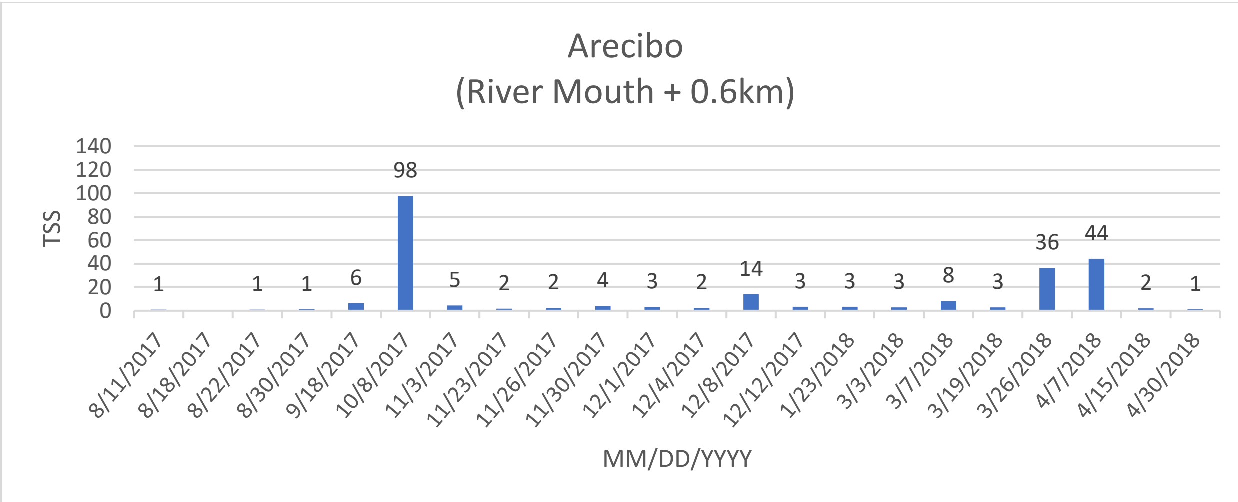
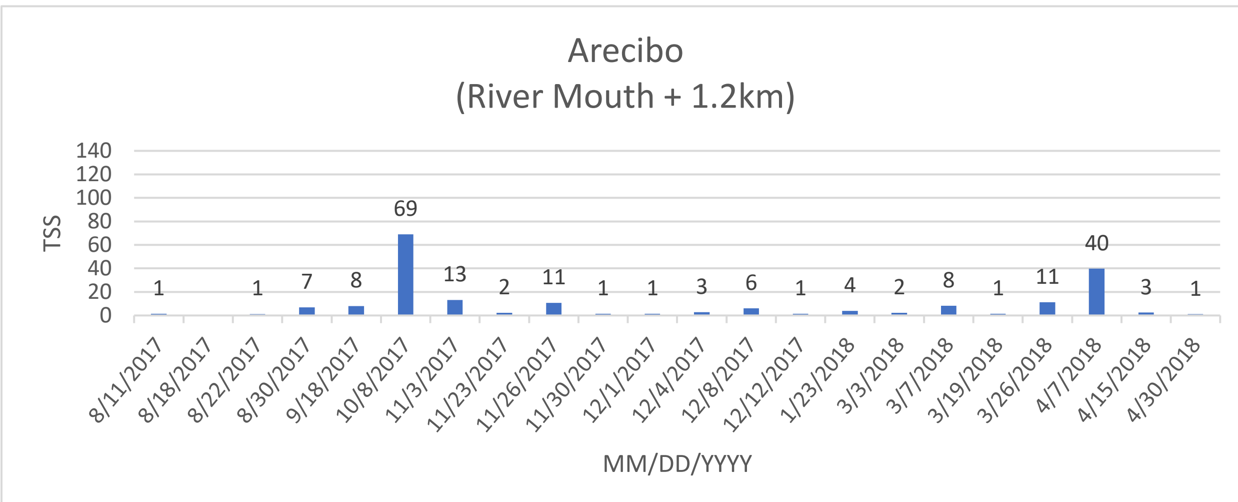


Figure 11. Results of Arecibo transect reference points along the river plume (set 1 of 3).





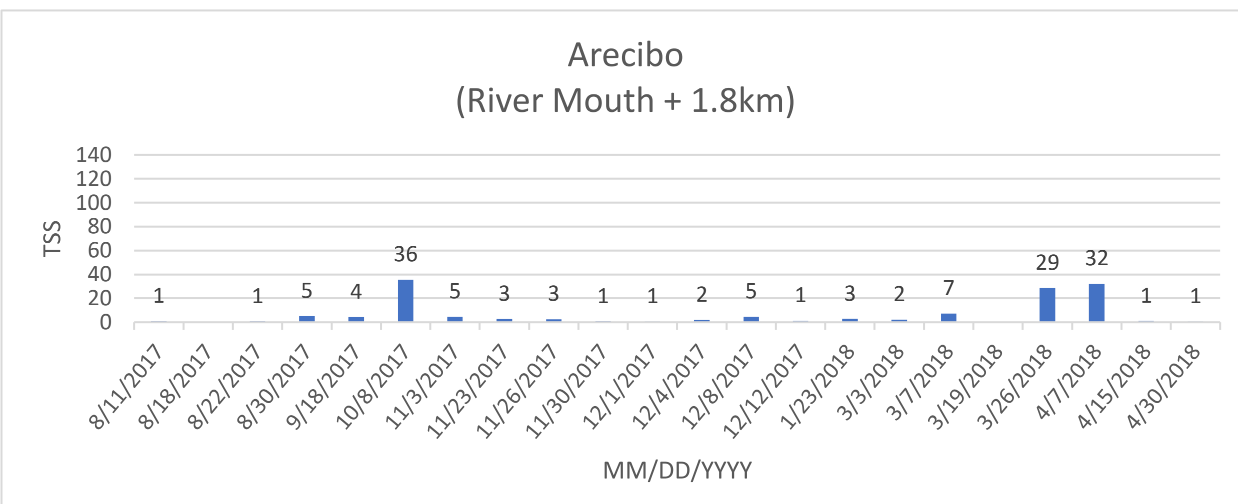
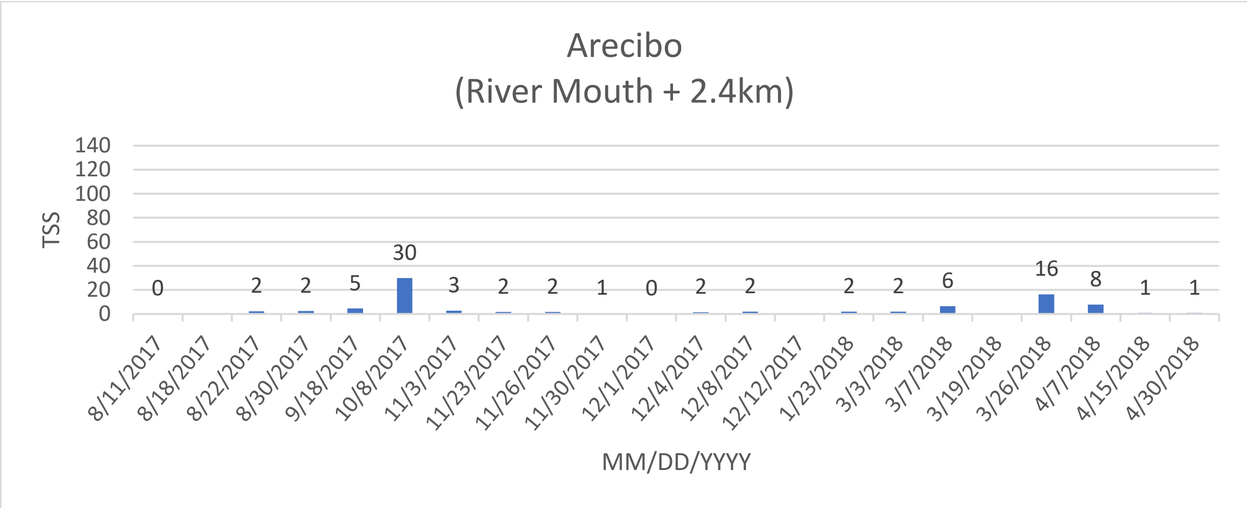


Figure 12. Results of Arecibo transect reference points along the river plume (set 2 of 3).



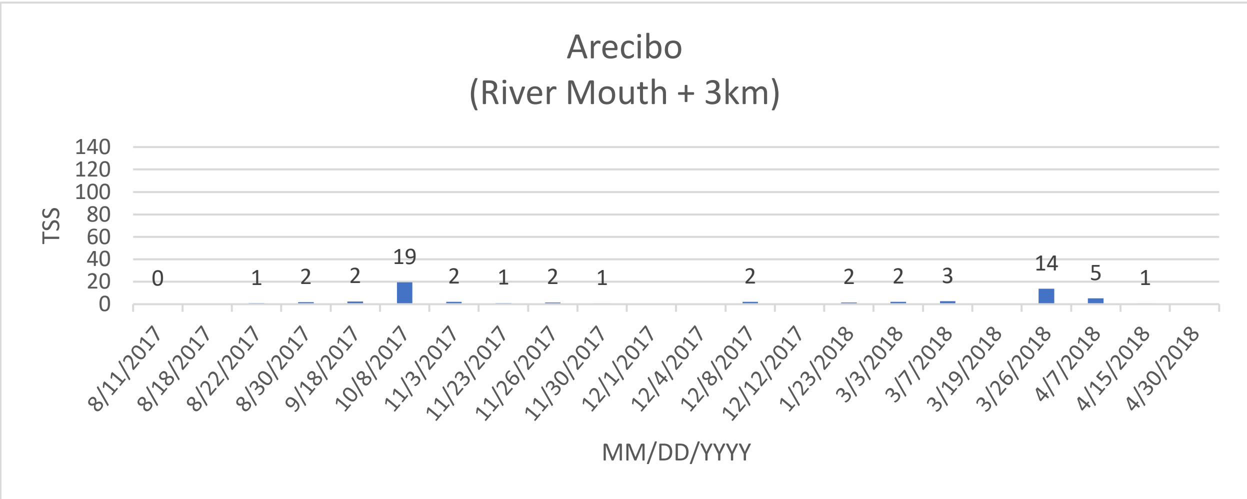


Figure 13. Results of Arecibo transect reference points along the river plume (set 3 of 3).

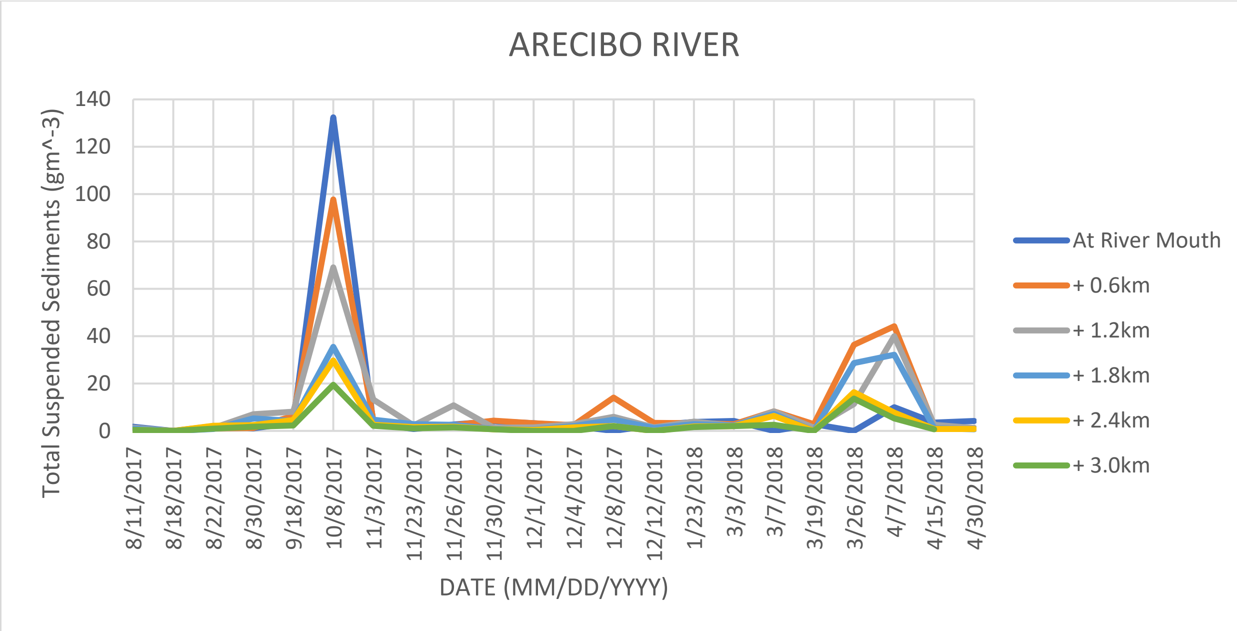


Figure 14. Results of Arecibo, all reference points along the river plume.

4.2.3 Comparison

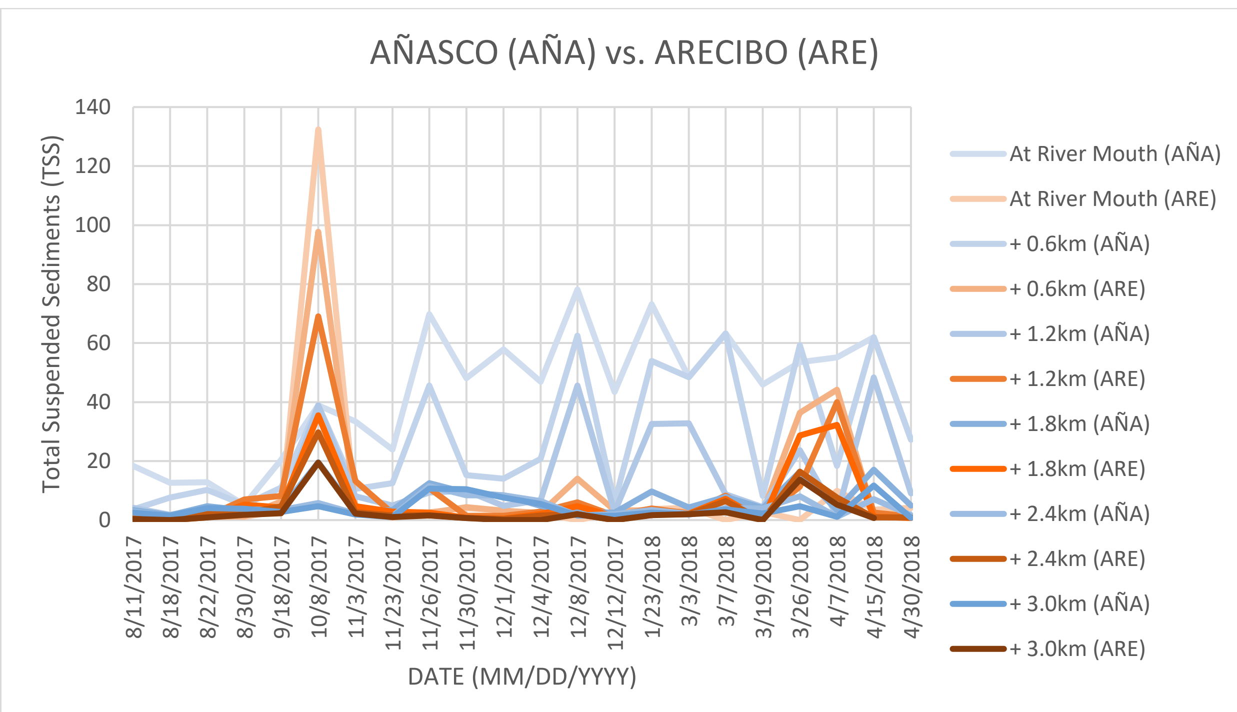
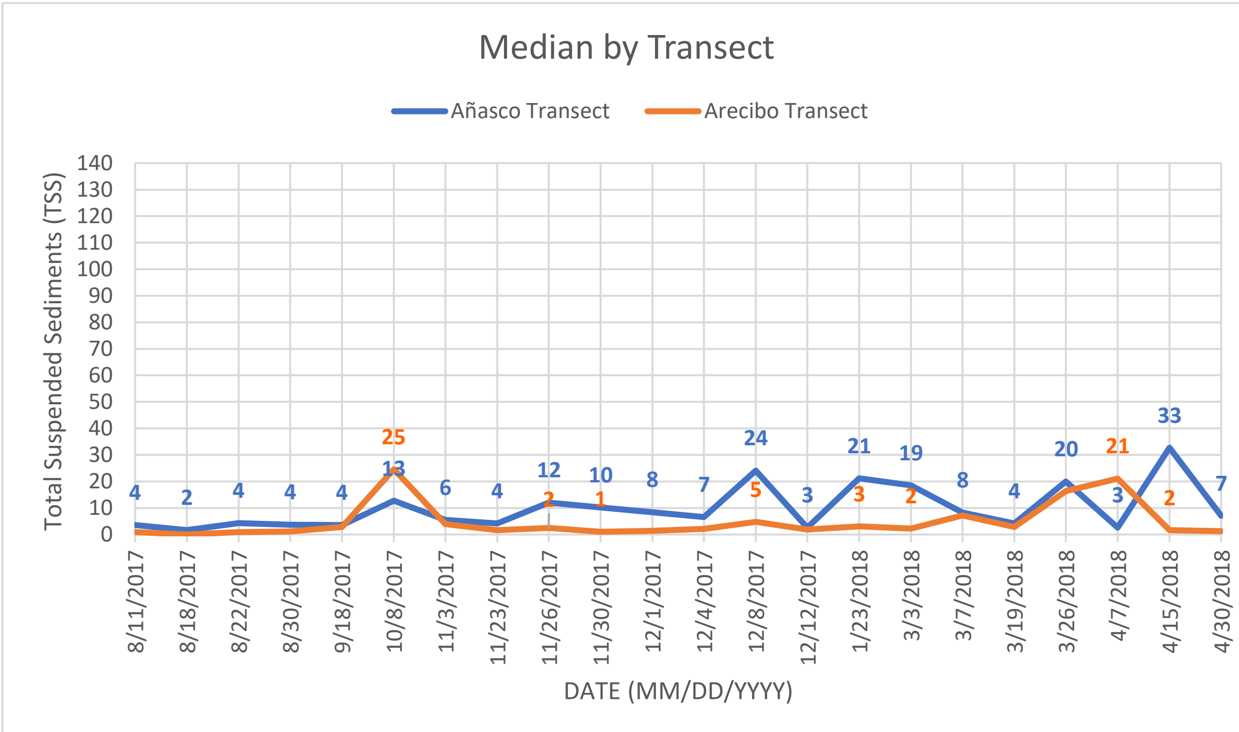


Figure 15. Results of all reference points along the river plume, including Añasco and Arecibo.

4.2.4 Statistical Analysis



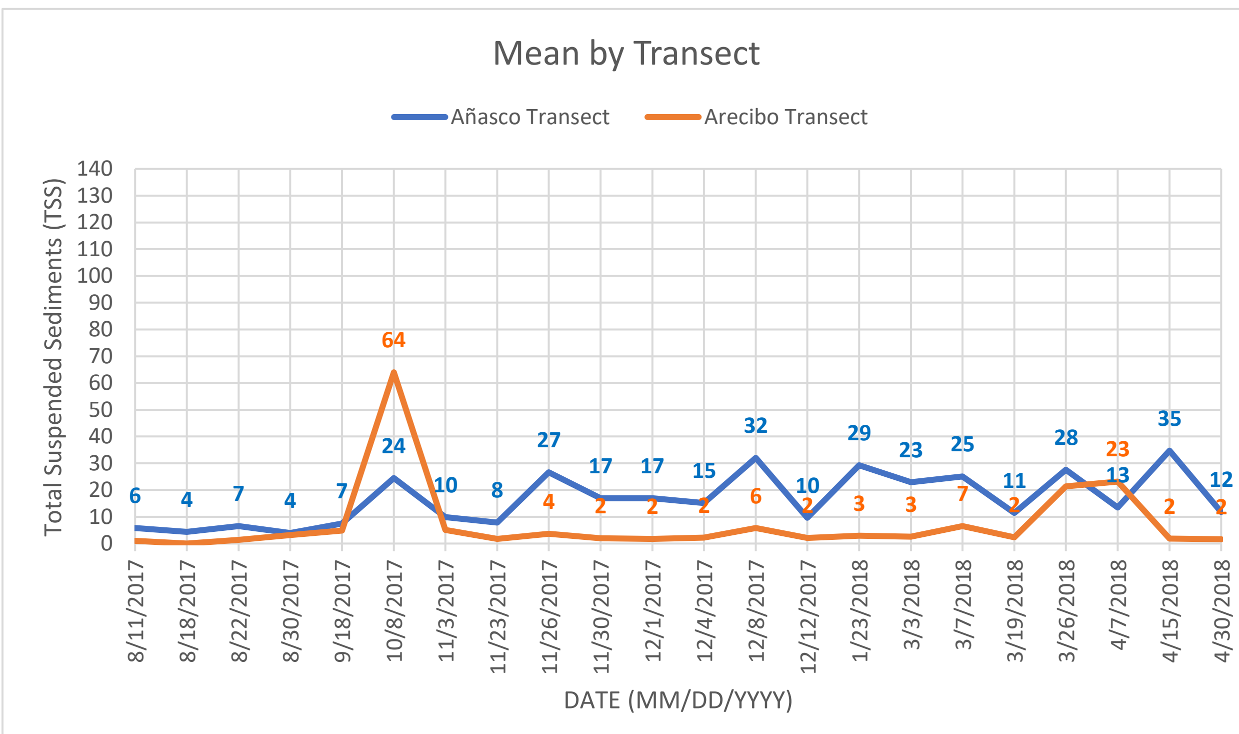


Figure 16. Statistical analysis for Añasco (blue) and Arecibo (orange). Upper: median, bottom: mean.

5. DISCUSSION

During major atmospheric and weather events, small dams and reservoirs like those in Puerto Rico play a relatively minor effect on the total sediment discharge to coastal marine waters (Warne et al., 2005). A past study comparing the concentration of sediments associated with Hurricane Georges (September 19th,1998) over Puerto Rico indicated that flood discharges entering coastal waters either mix with ocean water or form a hypopycnal or hyperpycnal plume (Warne et al., 2005). When observing the satellite imagery and the total suspended sediment values throughout this study, a combination of hypo and hyperpycnal plume may have occurred on October 08, 2017. On this date, higher concentrations of suspended sediments were observed compared with August (*before*) and mid-November (*after*). These concentrations may be directly influenced by slope failures triggered by Hurricane Maria's passage over Puerto Rico. In addition, another sediment transport process to consider is the resuspension of bottom sediments associated with storm surges and winds (Zhu and Wiberg, 2022). Therefore, the resuspension of sediment deposits may also cause a significant increase in the suspended sediment supply observed on October 08, 2017.

Interpreting the median statistical analysis serves as a descriptive figure to observe measurements between this study's two (2) locations. The next peak of suspended sediment concentrations was identified in mid-November, on the 26th of 2017. Even though it was expected to observe high concentrations in November, the sediment increase was significantly higher in Río Grande de Añasco over Arecibo. The site of Añasco for mid-November showed that its concentration was 3 (three) times the concentration reported on the previous date. It went from 4 gm^{-3} to 12 gm^{-} On the other hand, the concentration in the transect of Arecibo went from 1.66 gm^{-3} to 2.44 gm^{-3}. As expected, mid-November peaks correspond to higher concentrations than the period ***before*** Hurricanes Irma and Maria. The increase in concentrations could be associated with the runoff generated from landslide events as carried through the watersheds. The suspended sediment concentrations were observed to increase again by December. On December 8, 2017, an increment was observed from 7 gm^{-3} to 24 gm^{-3} for Añasco, and for the Río Grande de Arecibo increased from 2 gm^{-3} to 5 gm^{-3}. Starting in 2018, higher concentrations are present and maintained from January to April for both locations.

Comparing these results with a USGS monitoring stream station, the discharge peaks correlated through the same period as this study. The highest peak in the discharge plot (cubic feet per second, ft^3/s) corresponds to September 18, 2017, the same date as the higher concentration in this study. The pattern in the discharge plot also compares to the month of October, but the USGS provides estimated data for that period.

6. SUMMARY

Tropical storms, cyclones, and hurricanes induce sediment transportation through the watersheds due to mass wasting events generated by high-intense precipitation and erosion. This study analyzed suspended sediment concentrations by delimiting a transect, which started at the river mouth to the Atlantic Ocean on both watersheds: Añasco (western) and Arecibo (central-western to north coast). The results show that the data from October is directly associated with Hurricanes Irma and Maria, events that generate extreme winds and storm surges. Previous studies established that storm surges initiate sediment resuspension. By validating the discharge from USGS data, the suspended sediment concentrations found from November to December may be directly influenced by events of mass wasting as an effect of the high-intensity rainfall from both hurricanes. These relationships are likely significant for predicting higher concentrations of suspended sediments near coastal waters.

7. ACKNOWLEDGEMENTS

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