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QUANTITATIVE ANALYSIS OF SUSPENDED SEDIMENTS AND CHLOROPHYLL-A IN COASTAL WATERS OF PUERTO RICO USING MERIS

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Abstract

This study survey the correlation between precipitation events, river discharge, and the dynamics of river plumes, in terms of their effect on suspended sediments and chlorophyll-a, in coastal areas of Puerto Rico. During August to November the greater amount of precipitation, and river discharge, has been documented (Gilbes et al., 1996). Therefore, it has been hypothesized maximum values of suspended sediments or total suspended matter (TSM) and chlorophyll-a (CHL) during the five strong rainfall events selected for this research and low concentrations during the event of almost none precipitation. Consequently, if more concentration of suspended matter and chlorophyll-a is registered it shall affects the coastal ecosystem and carbonate production. Through this research the suspended matter and chlorophyll-a concentrations were determined using a sensor on the ENVISAT-1 of the European Space Agency that has a spectral resolution of 300 meters, called Medium Resolution Imaging Spectrometer (MERIS). The data extracted from the images of MERIS, were submitted to an analysis of variance (ANOVA), and corroborate the hypothesis. Therefore it can be concluded that strong rainfall events will produce high river discharges that will bring more suspended sediment to the coasts; that suspended sediment concentration will decrease while it moves from on shore to offshore and that the relation between the suspended sediment and chlorophyll-a is strong and direct.

Key words: Total suspended matter, River discharge, River plumes, MERIS

Introduction

Intense precipitation events are responsible for the mainstream of the suspended sediments, and nutrient fluxes in the streams that eventually go to the ocean (Hoover and Mackenzie, 2009). Storms also cause landslides, which are a source of soil erosion and sediments yield in the catchments (Hone-Jay et al., 2013). The land use will affect and make some changes in the fluvial fluxes, specifically in the suspended sediment, the nutrients and the water (Hoover and Mackenzie, 2009). A storm or an intense precipitation event will bring to the ocean large inputs of dissolved particulate material and could be unfavorable to photosynthetic organisms because there will be low light, turbidity increase, rapid mixing of plumes which result in dilution of nutrients (Hoover and Mackenzie, 2009; Devlin et al., 2012). This factors could cause medium to long term impacts, such as reduce the densities of juvenile corals, changes in community composition, decreased species richness and changes to communities that are dominated by more resistant coral species and macroalgae (Devlin et al., 2012). Also, turbidity inhibits carbonate production due it reduces the amount of light reaching the sea floor affecting the growth of calcareous algae, sea grass and any photosynthetic organism such as phytoplankton (Tucker and Wright, 1991). Therefore, it is important to study the relationship between storm or strong rainfall events with the river discharge and the dynamics of river plumes around the coast of Puerto Rico. From August to November, there is high precipitation in the island, and large river discharge, therefore maximum values of suspended sediments and chlorophyll-a has been registered (Gilbes et al., 1996). Therefore, it has been hypothesized maximum values of suspended sediments or total suspended matter (TSM) and chlorophyll-a (CHL) during the five strong rainfall events selected for this research and low concentrations during the event of almost none precipitation. Consequently, during the wet season high concentrations of suspended sediments and chlorophyll-a are expected to be registered which affect the coastal ecosystem and carbonate production (Tucker and Wright, 1991).

Flood plume waters are buoyant freshwater masses and are found in the surface layer until it dispersed or it mixed into the water column (Devlin et al., 2012). This is why water sampling is collected on the top surface layer of the flood plumes, and remote sensed data recovered from surface water can be used to describe river plumes (Devlin et al., 2012). Based on water quality parameters that can be measured from space, ocean color satellite imagery offers large scale information of the river plume spatial and temporal distribution (Devlin et al., 2012). Remote sensing methods are relatively cost effective and detects, monitor and gather a variety of information (Devlin et al., 2012).

The Medium Resolution Imaging Spectrometer (MERIS) is the ocean color sensor used in this study, on board the ENVISAT-1 satellite of the European Space Agency and had a spatial resolution of 300 m which made it the first ocean color sensor adequate for monitoring coastal areas (Kratzer et al., 2008). Figure 1 shows an example of the TSS images produced by MERIS where the red color represents large amounts of suspended matter and chlorophyll-a and the white color represents low concentration. The sensor has a spectral resolution of 15 programmable spectral bands (Kratzer et al., 2008). After atmospheric correction, the MERIS Case 2 water algorithm uses remote sensing reflectance above surface in eight of the fifteen bands (Kratzer et al., 2008). The eight bands used for deriving the level 2 products are centered at 412, 442, 490, 510, 560, 620, 665 and 708 nm (Kratzer et al., 2008). The software called BEAM (http://www.brockmann-consult.de/cms/web/beam/) was used for processing the MERIS data, which is an open source application to visualize, analyze and process the data (Kratzer et al., 2008).

During the undergraduate research conducted last semester, the intense rainfall events and the images from MERIS were selected and processed using BEAM. A visual analysis was made for the suspended matter and chlorophyll-a concentrations using the color manipulation tool and applying a color palette, where the colors represents the maximum and minimum values. The red color was for the high concentration and light blue was for low concentration. Comparing the accumulated precipitation of the events and the river discharges, they agreed with the highest values of suspended matter and chlorophyll-a concentrations seen in the MERIS images (Vargas, 2014). A qualitative analysis and comparison was made between the suspended matter and chlorophyll-a concentrations, in both images they are intrinsically related because where the suspended sediments concentration was high the chlorophyll-a concentration was also high (Vargas, 2014). However, a quantitative analysis is needed to reach a well grounded conclusion. For this reason, through this project using the same processed images from MERIS, data from rainfall and rivers discharges is intended to perform such analysis that will give to this study a more reliable and accurate data.

The objectives of this research are: (1) establish the spatial and temporal variability of suspended sediments and chlorophyll-a in six streams of Puerto Rico, (2) evaluate suspended sediments and chlorophyll-a concentrations before and after several strong rainfall events, and (3) determine the relationship between rainfall, river discharge and the plume dynamics in the coast of Puerto Rico.

Study Sites

The area of interest is all the rivers in Puerto Rico that discharge into to the Atlantic Ocean and the Caribbean Sea. But since there are too many rivers in Puerto Rico, the island was divided into four sections (North, South, East and West), and the rivers selected for this study were *Río Grande de Arecibo*, *Río La Plata*, *Río Jacaguas*, *Río Grande de Patillas*, *Río Grande de Añasco* and *Río Fajardo*. Figure 2 shows the location of the rivers on a map of Puerto Rico.

As the name suggest Rio Grande de Arecibo is in the town of Arecibo. The valley floor of the Rio Grande de Arecibo has a gently slope with an elevation approximately of 80 feet above sea level. Throughout the Arecibo- Manatí region alluvial, blanket sand, swamp and beach deposits of Quaternary age overlie the limestone formations. The alluvial deposits are composed of moderately well sorted stratified sand, gravel, silt and clay. The thickness of the alluvial deposits within the Rio Grande de Arecibo valley average about 130 feet thick in the southern part of the valley. Also, the river deposits blanket sands, which are composed of quartz and clay varying greatly in proportions (Veve and Taggart, 1996). The other river in the North which will be study is the longest river (62 miles) in Puerto Rico, the Río La Plata, in which its flood plain is in the Vega Baja Town. The headwaters of Rio La Plata are at an elevation of 2,960 feet. Alluvial deposits of 110 feet thick are found along stream valley, and in the coastal plain are swamp and marsh deposits. Pleistocene silica sand deposits form most of the ridge of the coastal terrace deposits, along the edges of the coastal plain (Veve and Taggart, 1996).

In the South one of the rivers that was studied is Rio Grande de Patillas in the town of Patillas. Quaternary alluvial deposits overlap the Juana Diaz Formation and are composed of layers of unconsolidated to poorly consolidated clay, sand, gravel and rounded to angular boulders. These deposits are the most important lithologic units in this region because it contains a considerable acquire (Veve and Taggart, 1996). The other river in the South was Rio Jacaguas in the Juana Diaz town. Alluvial deposits of Quaternary in age overlie the Juana Diaz Formation and Ponce Limestone. These deposits consist of poorly bedded and sorted gravel, sand, silt, and some clay. The thickness of these alluvial deposit ranges from 200 to 2,000 feet (Veve and Taggart, 1996).

In the West side the Rio Grande de Añasco was analyzed, which is locating in the Añasco town. In its valley are volcanic and volcaniclastic rocks of Cretaceous age which are overlain by Quaternary alluvial deposits. The alluvial fill in the valley is composed of clay, silt, and sand with gravel deposits also thin corridors of alluvium have been deposited along the Rio Grande de Añasco. Swamp deposits are present in the valley (Veve and Taggart, 1996).

In the East the river selected was Rio Fajardo and the flood plain alluvium is mostly unconsolidated, poorly sorted to moderately well sorted, commonly thick bedded sand, gravel and clay. In the valley of Rio Fajardo the flood plain forms piedmont plains with a thickness of 35 m (Briggs and Aguilar-Cortés, 1980).

Methods

Previously, as described in Vargas 2014, the images from MERIS were downloaded from NASA's ocean color website(http://oceancolor.gsfc.nasa.gov/cgi/browse.pl?sen=me&typ=FRS). The study period covered 5 of the 10 years of MERIS operation, from April 2002 until April 2012. In this period approximately five events of intense rainfall were selected and one image with almost no precipitation was chosen for comparison. Preliminary, 18 rainfall events were chosen, then while selecting the cloud-free images from MERIS this number was reduced to 5 events. The images days are: Nov 23, 2007; Oct 19, 2008; Sep 18, 2009; Nov 17, 2009 and Oct 18, 2010 (Figure 3 & 4). A combination of rainfall data from the National Weather Service (NWS) and the available cloud-free images from MERIS were used to identify the selected events (Figure 5). After the images were downloaded they were processed using the BEAM software and the MERIS Case 2 Regional Processor, which has 3 different algorithms and the final products are the concentration of suspended sediments and chlorophyll-a. Also, the stream discharge data from the available USGS gauging stations in selected rivers were downloaded from the USGS website (http://pr.water.usgs.gov/). The discharge, which is measured in the middle of the basin and not in the mouth of the river, will be an important consideration at the time of the analysis (Graph 1, 2, 3,4 &5).

During this new study, initially, a total of 30 transects were created (5 transects per river) to extract the numerical data from the processed images. Subsequently, statistical analysis such as analysis of variance (ANOVA) were performed using the stream discharge from the USGS, and the dynamics of the river plume from MERIS data (suspended matter and chlorophyll-a concentration), with the purpose of establishing the relationship between them. A correlation analysis of the data was produced in Excel for every rainfall event and the almost no precipitation event.

Statistical analysis, between transects per river were done to evaluate the variability of suspended sediments and chlorophyll-a in the six streams, *Río Grande de Arecibo*, *Río La Plata*, *Río Jacaguas*, *Río Grande de Patillas*, *Río Grande de Añasco* and *Río Fajardo*. Then, to determine the river plume behavior between rivers in the same precipitation event an average transect was calculated from the five transects of the river. This average transect was used to made the comparison between the rivers and for the analysis of variance. The third statistical analysis was between the six rainfall events 2007 NOV 23, 2008 OCT 19, 2009 Feb 4, 2009 NOV 17, 2009 SEP 18, and 2010 OCT 18, using the average transect of every river.

Sample description

The island of Puerto Rico was divided into four sections: North, South, East, and West to carry out the sampling and quantitative analysis of the plumes. Two rivers from the North and South: the *Río Grande de Arecibo* and *Río La Plata* in the North, and *Río Jacaguas* and *Río Grande de Patillas* in the South. In the East and West of the island one river was selected due to the short dimension of those sections. The *Río Grande de Añasco* in the West and *Río Fajardo* in the East. Table 1 shows the coordinates of the river mouth for the selected rivers in this study.

Several visualization analysis of the plumes were made last semester using BEAM. In this new project quantitative analysis of suspended matter and chlorophyll-a were developed by creating a grid from inshore to offshore waters. Initially, in this grid 5 transects with a length of 40 kilometers were made, starting from the mouth of the river through the bay. At the end of the 40 km transects, a distance of 7.5 km between each transect was determined. Using BEAM's pixel extraction tool in each transects the suspended matter and chlorophyll-a concentration was extracted from every MERIS images.

Results

Statistical Analysis between transects of each river

Each river plume behavior was determined by evaluating the variability of suspended sediments and chlorophyll-a in the six streams, *Río Grande de Arecibo*, *Río La Plata*, *Río Jacaguas*, *Río Grande de Patillas*, *Río Grande de Añasco* and *Río Fajardo*. In each river five transects were conducted with seven points each. Those transects were compared with each other to see how the points from the mouth of the river through 40 km away varied. Except for the *Río Fajardo* were transects measure 25 km long due to its proximity to Vieques y Culebra islands. The results of the analysis of variance (ANOVA) between the points from on shore to offshore in transects of each river showed that points in transects vary significantly. Except for the Río Fajardo on 2009 FEB 4, where some data is missing due to the presence of clouds.

Statistical Analysis between rivers

To compare the dynamics of the river plume between the rivers in the same rainfall event the average of the 5 transect was obtained to create a single transect per river. Comparing the average transect between rivers it shows that there is a significant variability between the rivers. In each rainfall event, 2007 NOV 23, 2008 OCT 19, 2009 NOV 17, 2009 SEP 18, 2010 OCT 18 and the almost none precipitation event 2009 Feb 4, this behavior was shown in the rivers. Table 2 shows if the ANOVA has significance or no significance. The table was constructed considering the obtained p-value, if the p-value was lower than α =0.05 the analysis has significance, if the p-value was higher, then it has no significance.

Statistical Analysis between rainfall events and no precipitation event

To determine the variability of the suspended sediments and chlorophyll-a between the five rainfall events and almost none precipitation event an analysis of variance (ANOVA) was made using the average transect of the river and comparing it with the others transects of the same river with the rainfall events. The analysis of variance showed that there is a significant variability of SS and CHL between the six events. (Table_) Except for the Río Fajardo, probably because in one event some data is missing due to the presence of clouds. Table 3 shows if the ANOVA has significance or no significance. The table was constructed considering the obtained p-value, if the p-value was lower than α =0.05 the analysis has significance, if the p-value was higher, then it has no significance.

Correlation

An analysis of correlation was made to establish the relation between the two variables: suspended sediment and chlorophyll-a, without distinguishing which one is the independent or dependent variable. The correlation measures if there is a linear association between both variables. The values of the correlation coefficient are between $-1 \leq r \leq 1$. If r is -1 or near the correlation is strong and inverse, which means if a variable increase the other variable decrease. If r is 1 or near the correlation is strong and direct, this means that if one variable increase the other one will increase too. If r is 0 or near the correlation is weak.

For the strong rainfall event on 2007 NOV 23 the correlation coefficient value was 0.923, which is near to 1. For the other strong rainfall events on 2008 OCT 19, 2009 NOV 17, 2009 SEP 18, and 2010 OCT 18 the value of the correlation coefficient was 0.998, 0.959, 0.997, 0.993, respectively. For the almost none precipitation event on 2009 FEB 4 the correlation coefficient value was 0.998. The correlation made for the five strong events and the almost none precipitation event showed a strong and direct relation between the suspended sediment and chlorophyll-a. This analysis was made without the outliers' values which are the observation points that are distant from the other observations. The outliers were eliminated for calculate the correlation because it could influence in the result. However, this was not the case but the same behavior was observed, a strong and direct relation between both variables. Graph 7 to 12 shows the correlation of the suspended sediments and the chlorophyll-a.

Discussion

The spatial and temporal variability of suspended sediment and phytoplankton chlorophyll-a in six streams of Puerto Rico, was established. Through the analysis of variance it has been determined that suspended sediment concentration will decrease while it moves from on shore to offshore. Evaluating concentrations of suspended sediment and chlorophyll-a before and after several strong rainfall events, it has been determined that during the strong rainfall events concentration of suspended sediment and chlorophyll-a are higher than the event with almost no precipitation. Although, in some rivers there were high concentrations of SS and CHL during the event with almost none precipitation, MERIS could detected high concentration values due to the re-suspended sediment caused by strong waves. Comparing the river discharge between the suspended sediment and chlorophyll-a concentration data extracted from the images from MERIS it has been corroborated that strong rainfall events will produce high river discharges that will bring more suspended sediment to the coasts, and suspended sediment concentration will decrease while it moves from on shore to offshore.

The relation between the suspended sediment and chlorophyll-a, is strong and direct, which means that if suspended sediment increase the chlorophyll-a will increase and if the suspended sediment decrease the chlorophyll-a shall decrease. This behavior happens due to rivers brings nutrients and that causes chlorophyll- increases. But sediments does not cause increase chlorophyll-a. The processes are parallel but it cannot be said that one cause the other.

Conclusion

The Medium Resolution Imaging Spectrometer (MERIS), a sensor on the ENVISAT-1 of the European Space Agency that has a spectral resolution of 300 meters is a reliable source to determine the suspended sediment and chlorophyll-a concentrations. Using MERIS and a software called BEAM maximum values of suspended sediment and chlorophyll has been registered. The data extracted from the images of MERIS, were submitted to an analysis of variance, and corroborate that suspended sediment concentration will decrease while it moves from on shore to offshore, that during the strong rainfall events concentration of suspended sediment and chlorophyll-a are higher than the event with almost no precipitation and that the relation between suspended sediment and chlorophyll-a is strong and direct. Therefore it can be concluded that strong rainfall events will produce high river discharges that will bring more suspended sediment to the coasts, and suspended sediment concentration will decrease while it moves from on shore to offshore.

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Figures

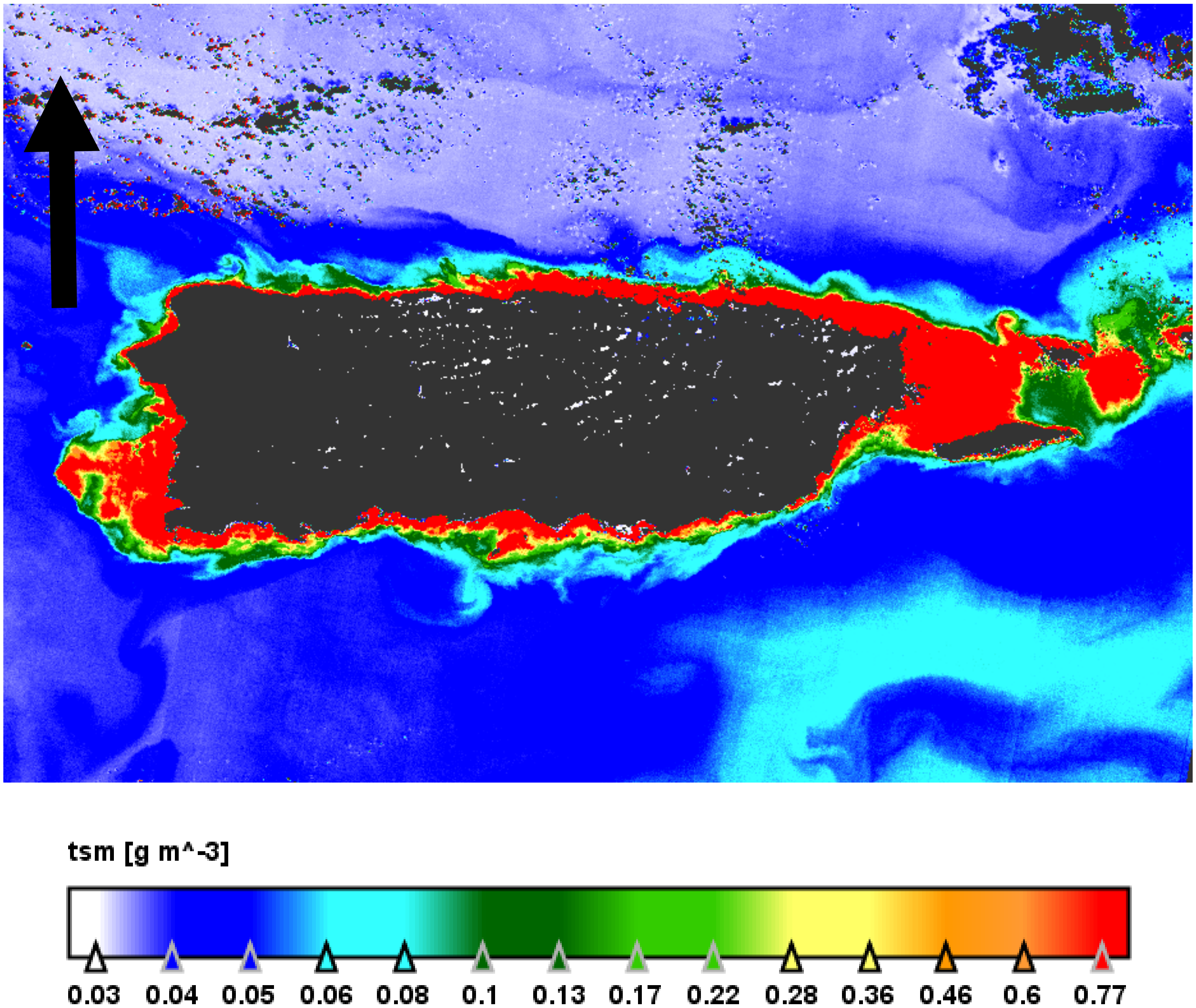


Figure 1. Processed image of Puerto Rico showing the mean of the suspended sediment concentration, the red color means high concentration and the white color represents low concentration.

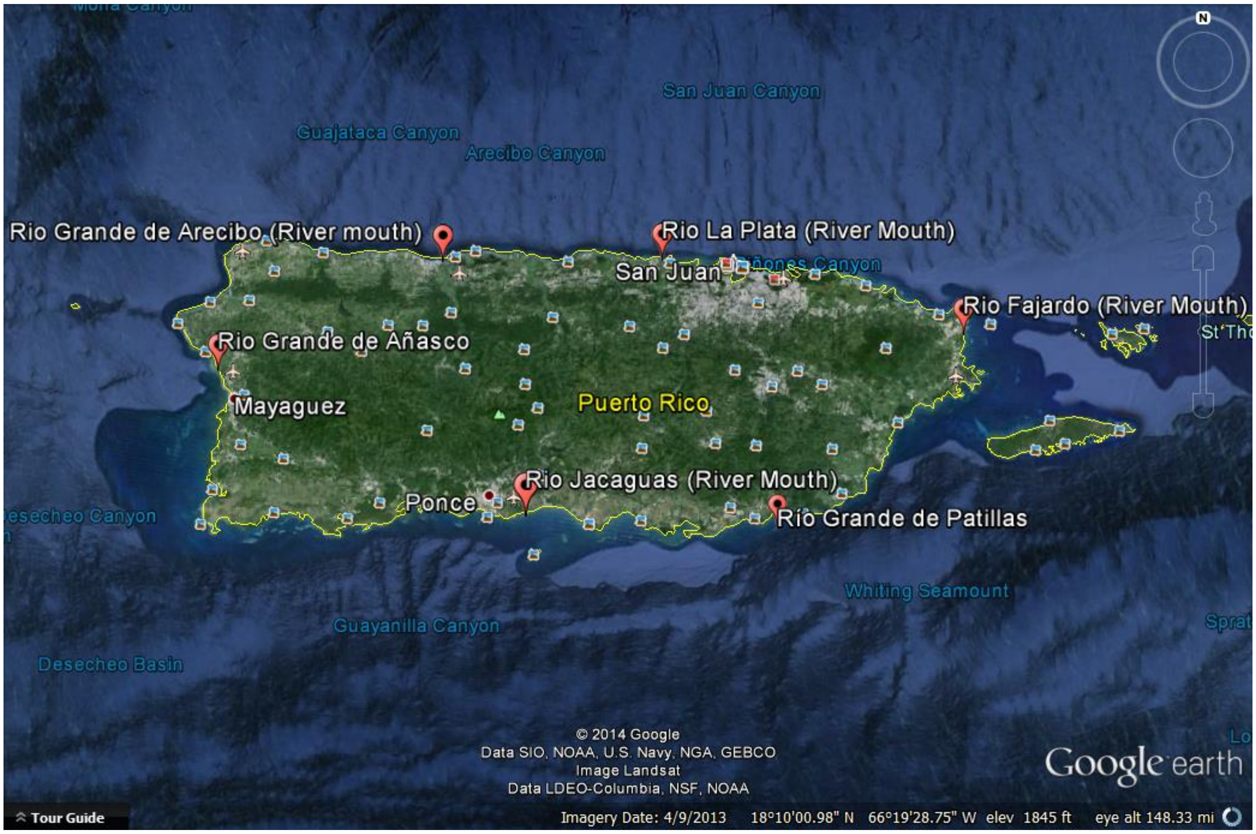


Figure 2. Location of the six streams of Puerto Rico: *Río Grande de Arecibo* (North), *Río La Plata* (North), *Río Jacaguas* (South), *Río Grande de Patillas* (South), *Río Grande de Añasco* (West), and *Río Fajardo* (East).

Suspended Sediment MERIS images

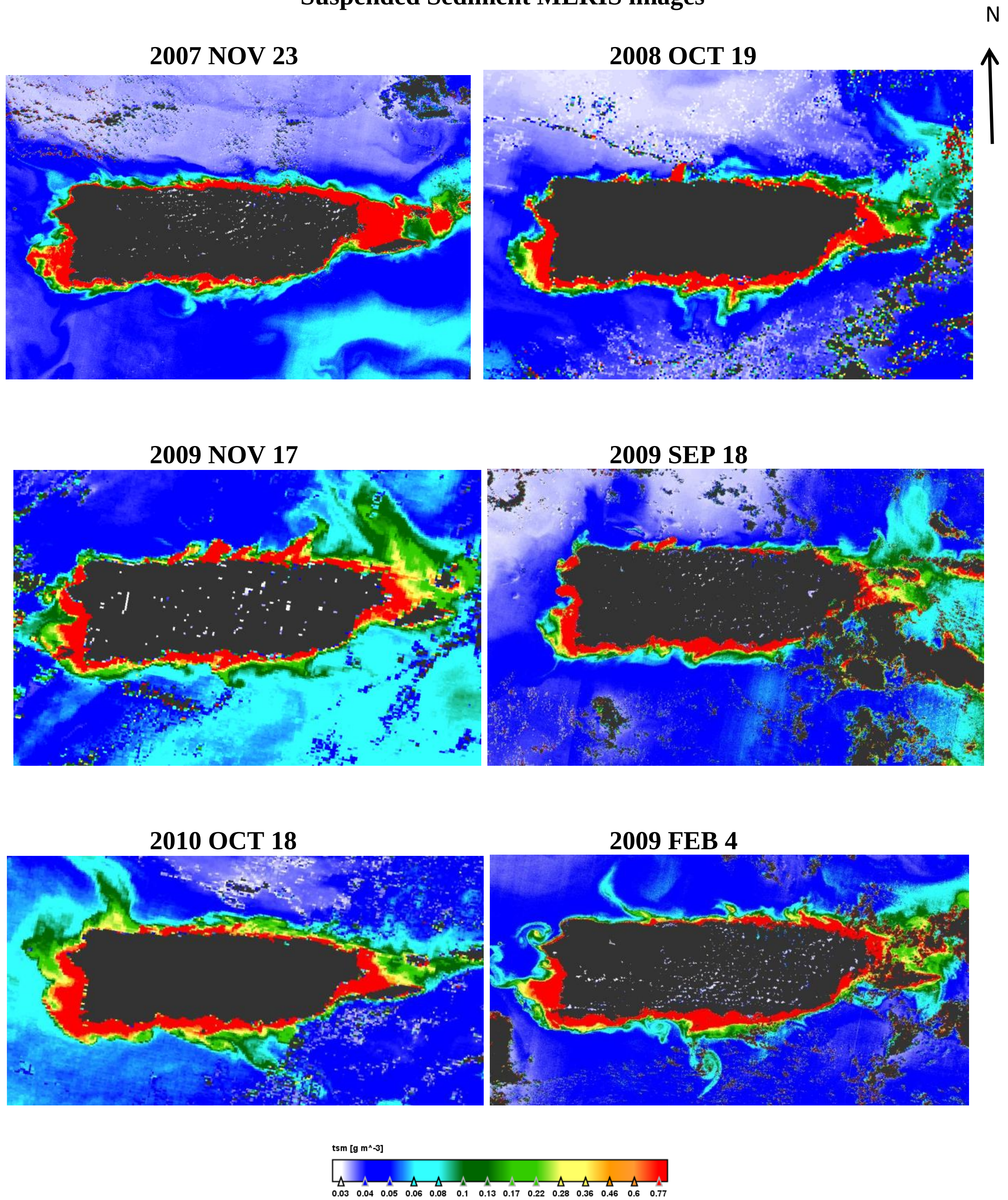


Figure 3. Processed MERIS images showing the suspended sediment during the five strong rainfall events (first five images) and the almost no precipitation event (2009 FEB 4). The red color means high concentration and the white color represents low concentration.

Chlorophyll-a MERIS images

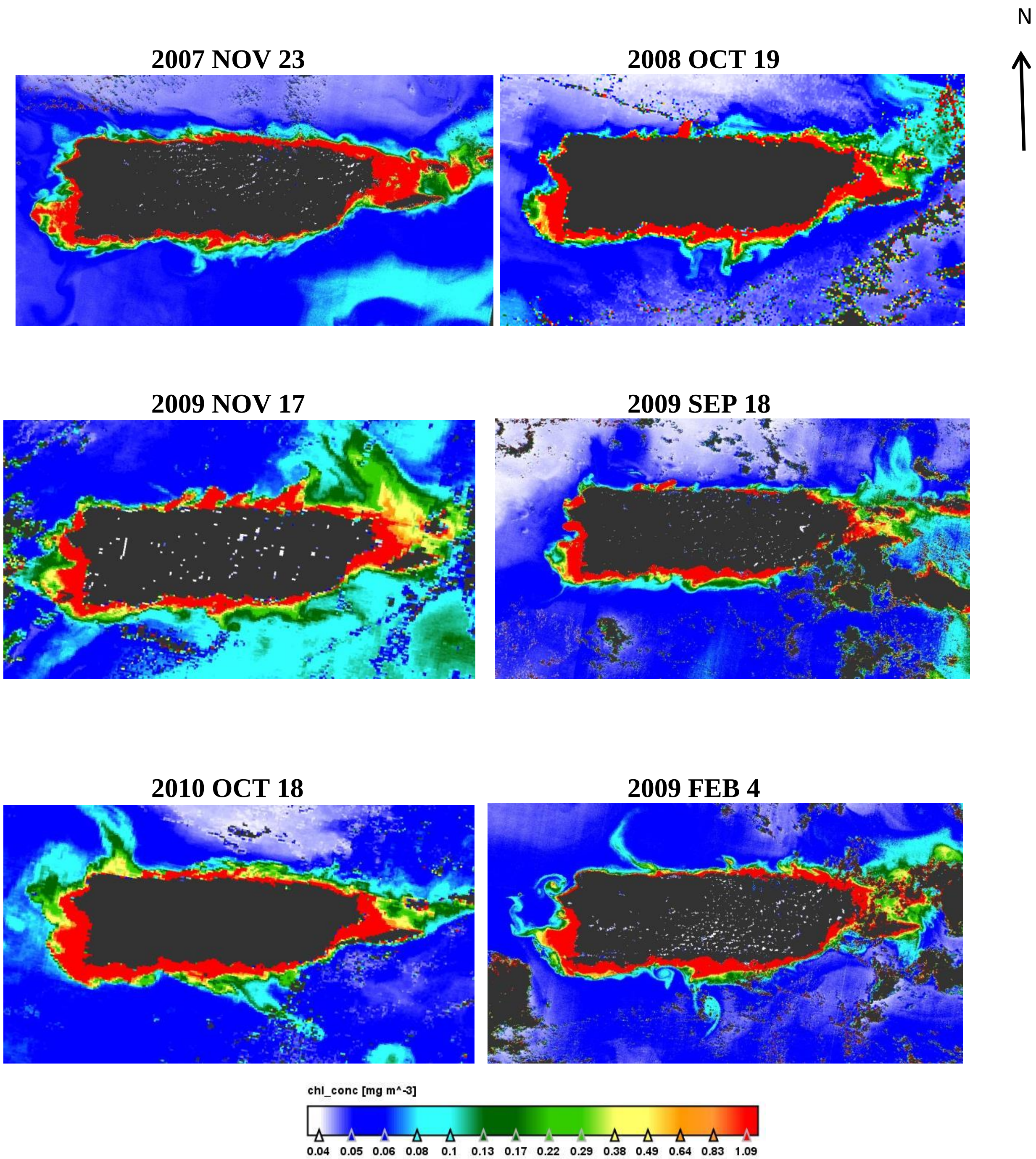
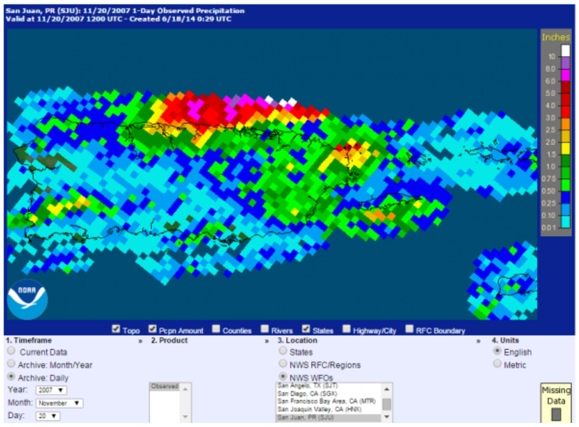


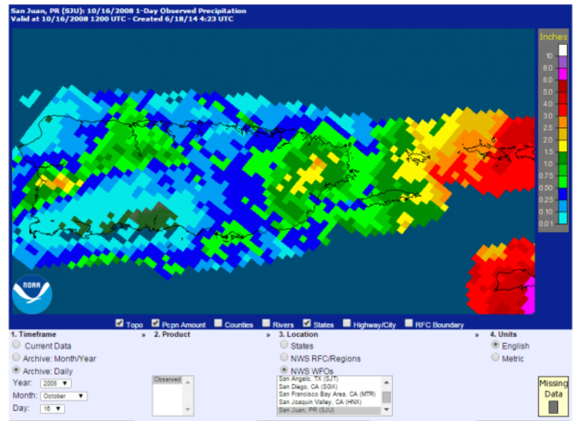
Figure 4. Processed MERIS images showing the chlorophyll-a during the five strong rainfall events (first five images) and the almost no precipitation event (2009 FEB 4). The red color means high concentration and the white color represents low concentration.

Precipitation data

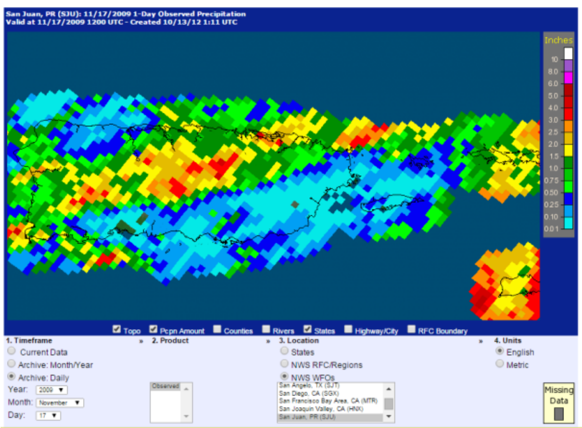
2007 NOV 20



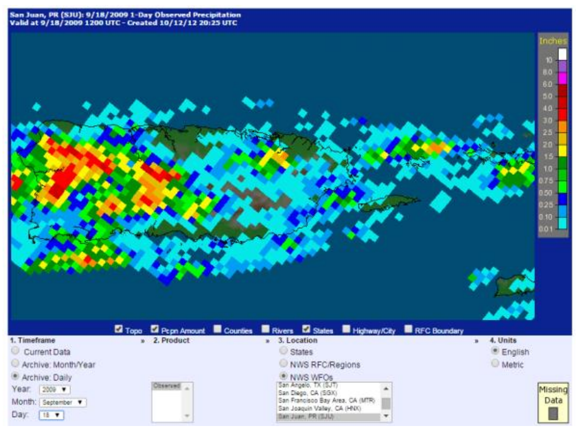
2008 OCT 16



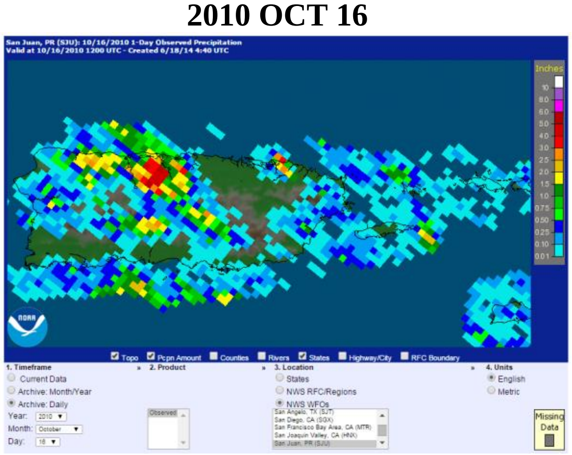
2009 NOV 17



2009 SEP 18



2010 OCT 16



2009 FEB 4

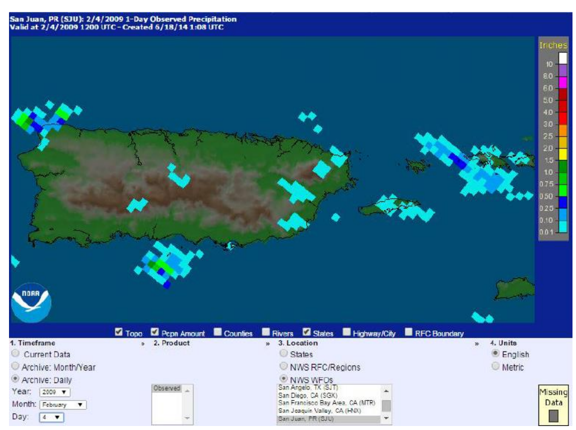
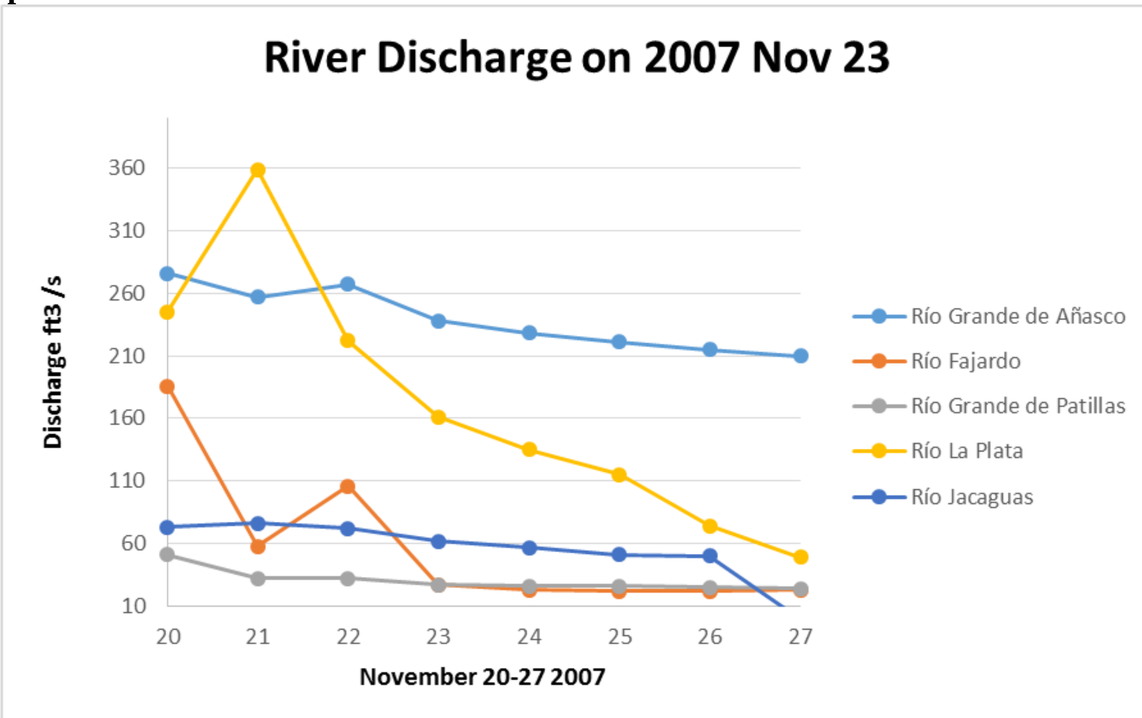
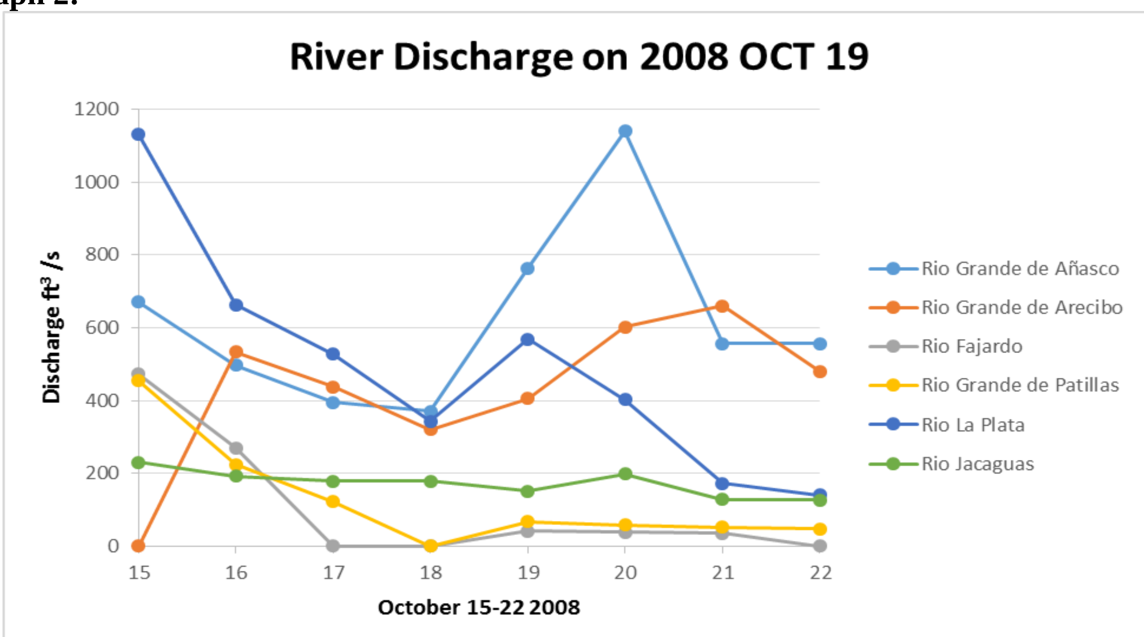


Figure 5 . Precipitation data of the five strong rainfall event (first five images), and the almost no precipitation event (2009 Feb 4).

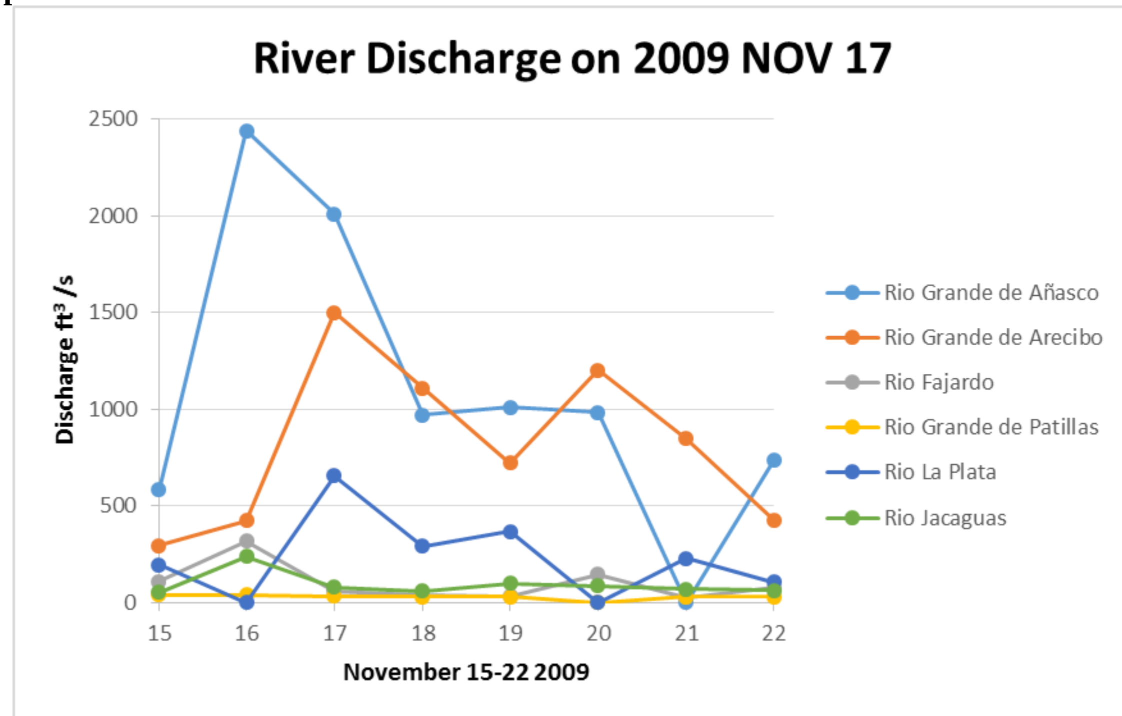
Graph 1:



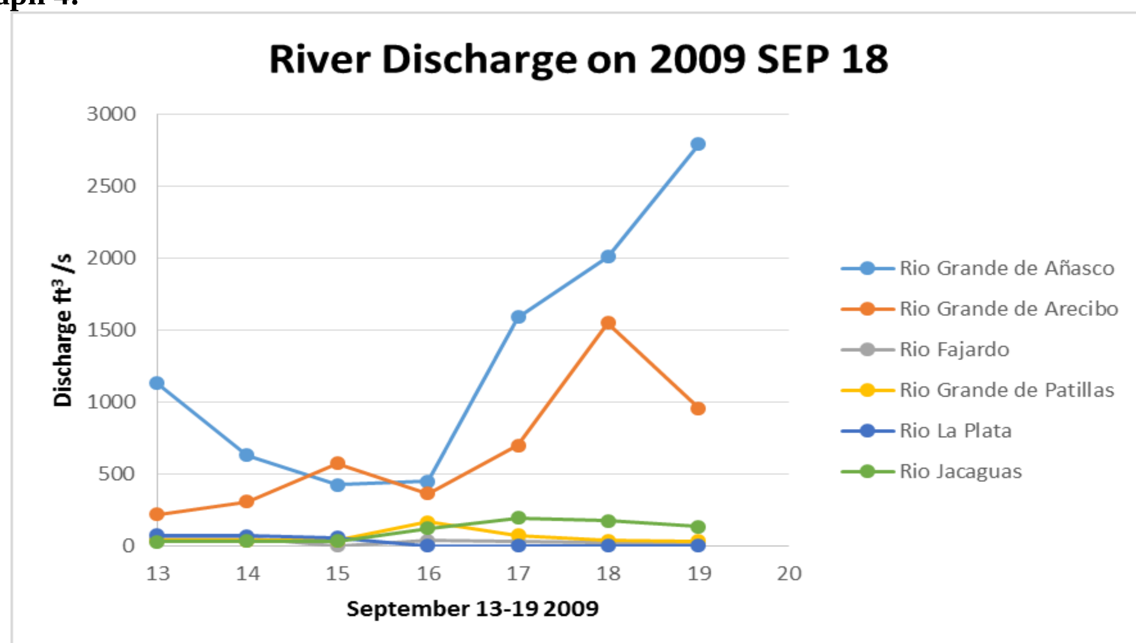
Graph 2:



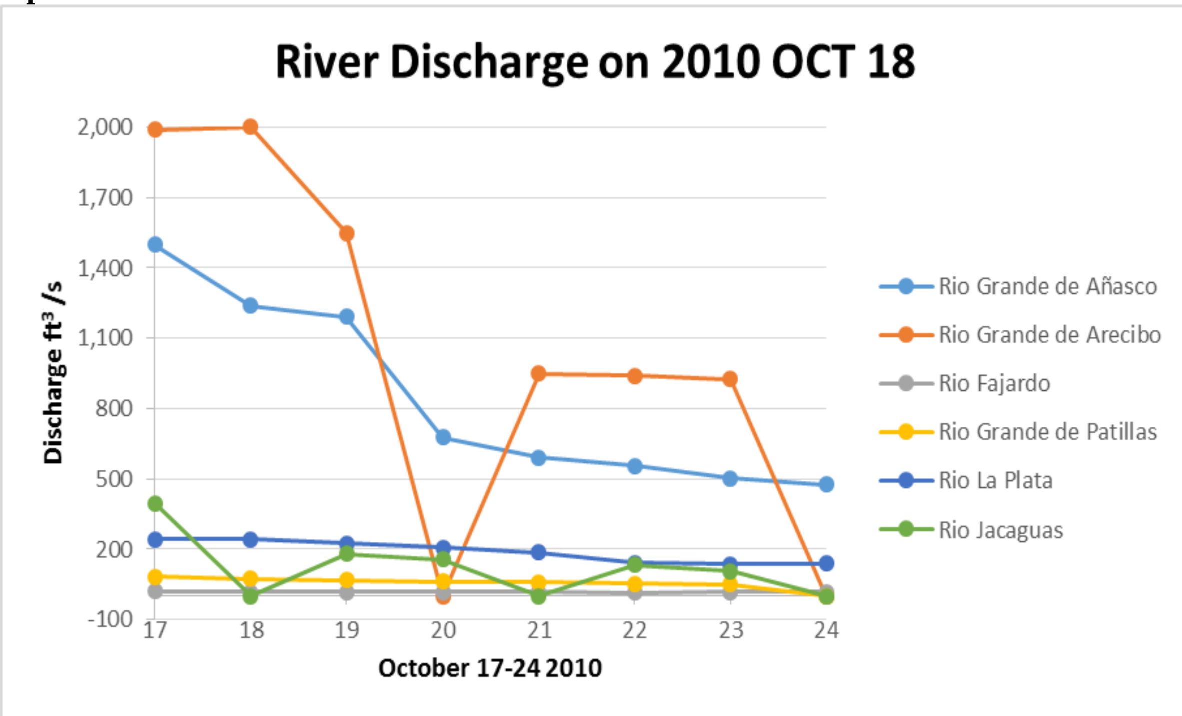
Graph 3:



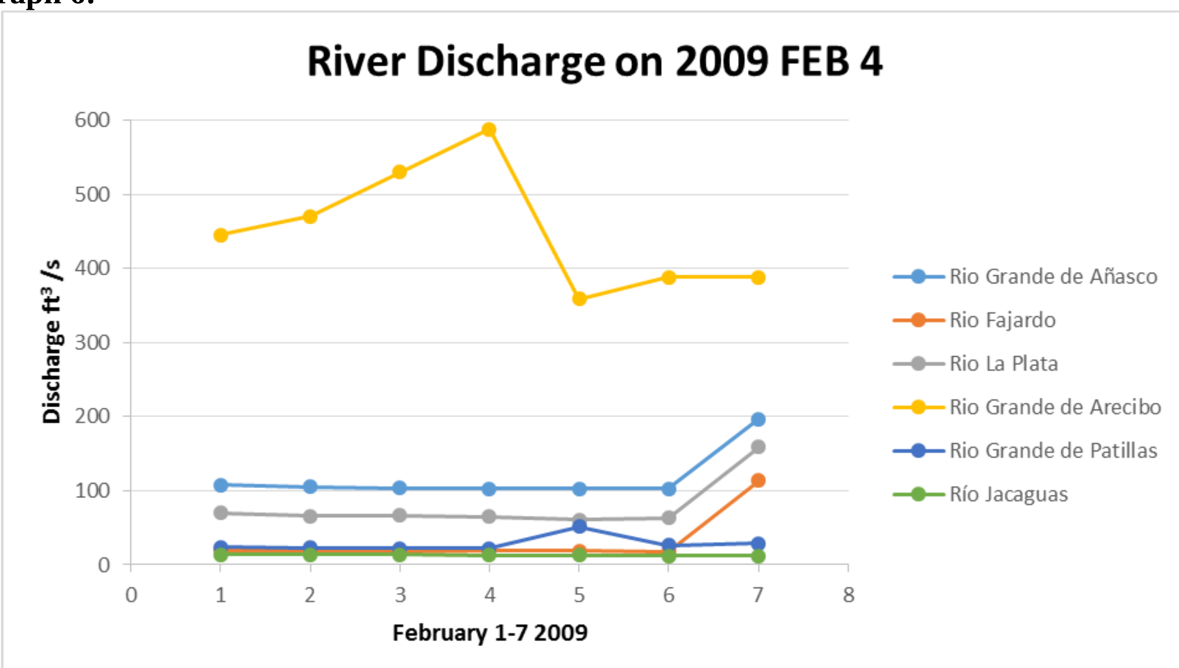
Graph 4:



Graph 5:



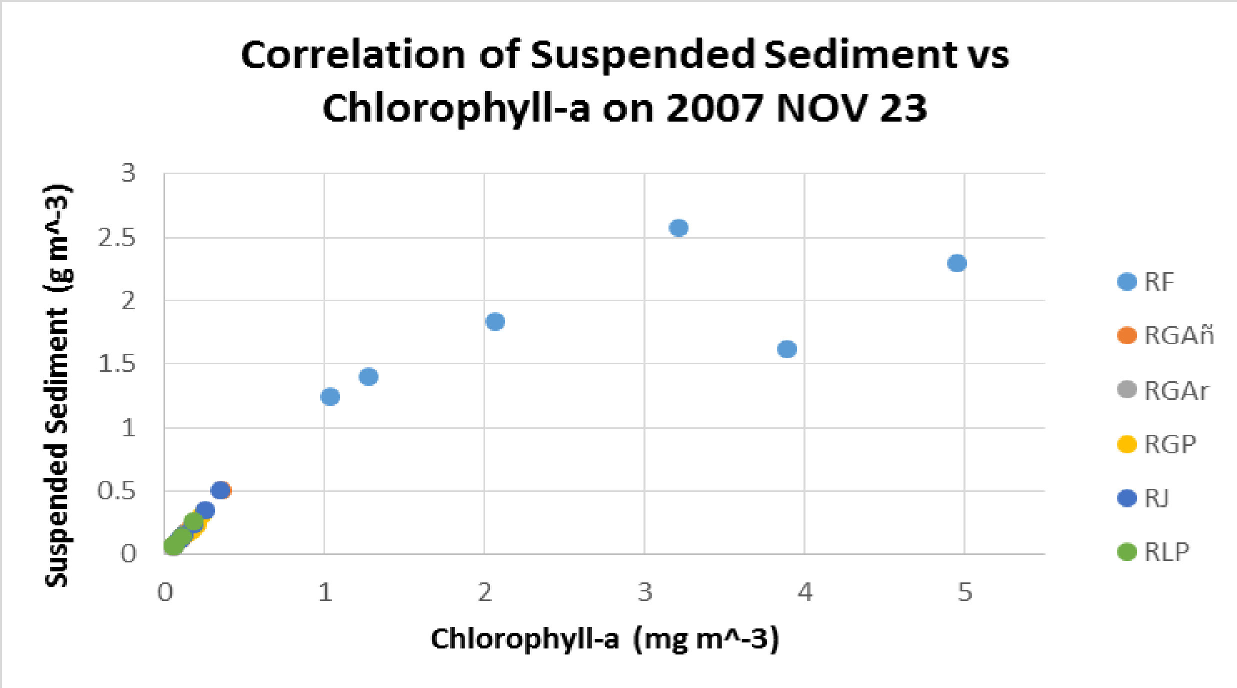
Graph 6:



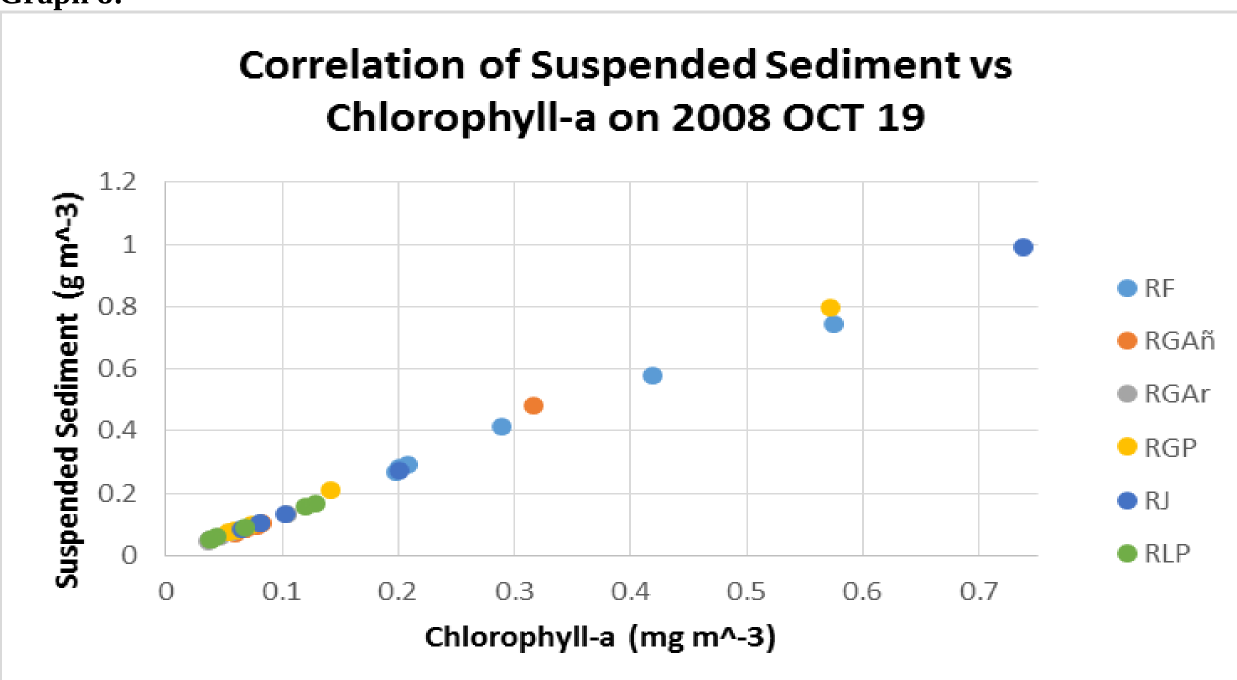
Graph 1, 2, 3, 4, 5, & 6: River discharge of every stream during the 5 strong rainfall events and the event with almost none precipitation (2009 FEB 4).

Correlation

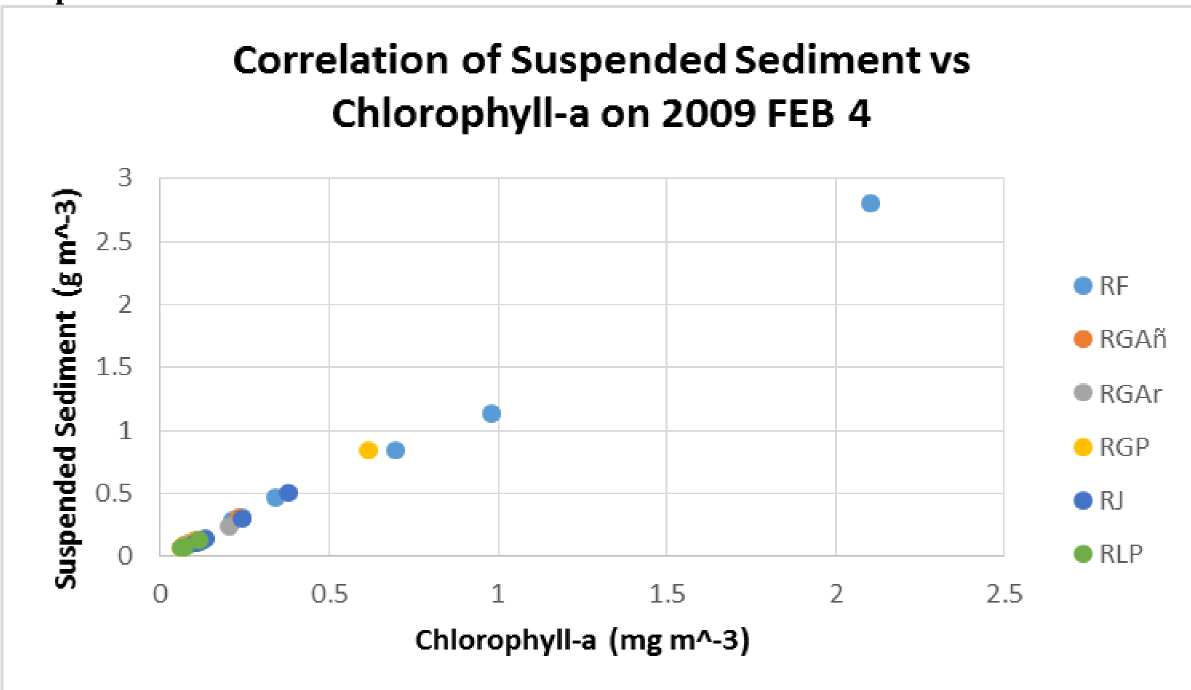
Graph 7:



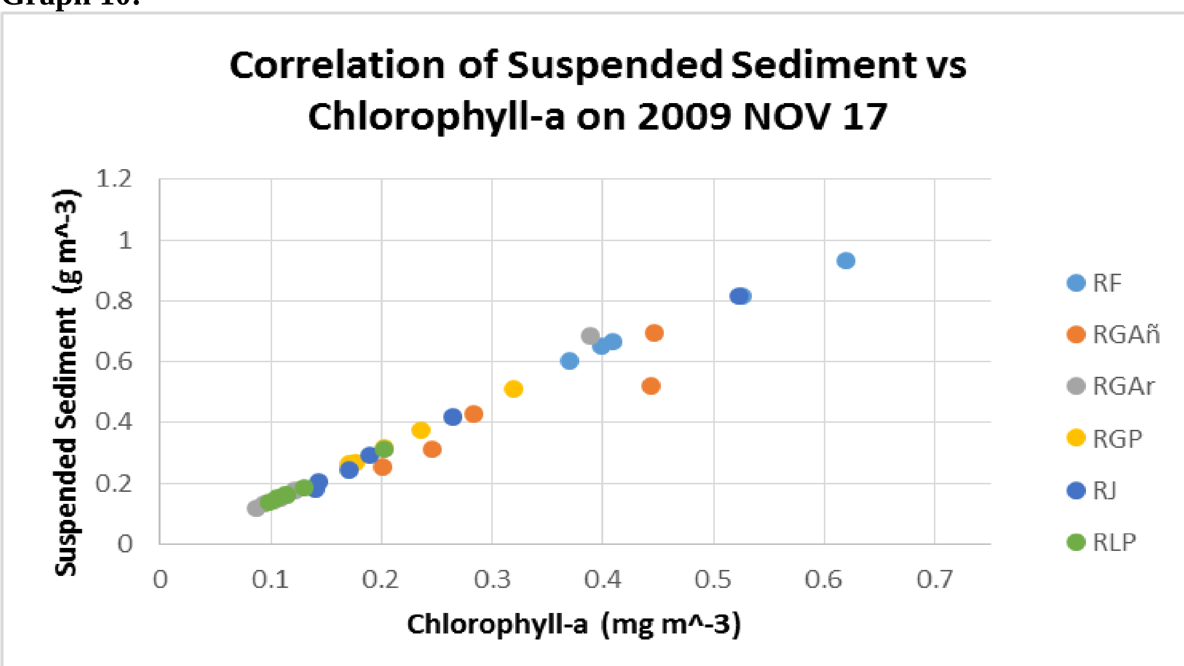
Graph 8:



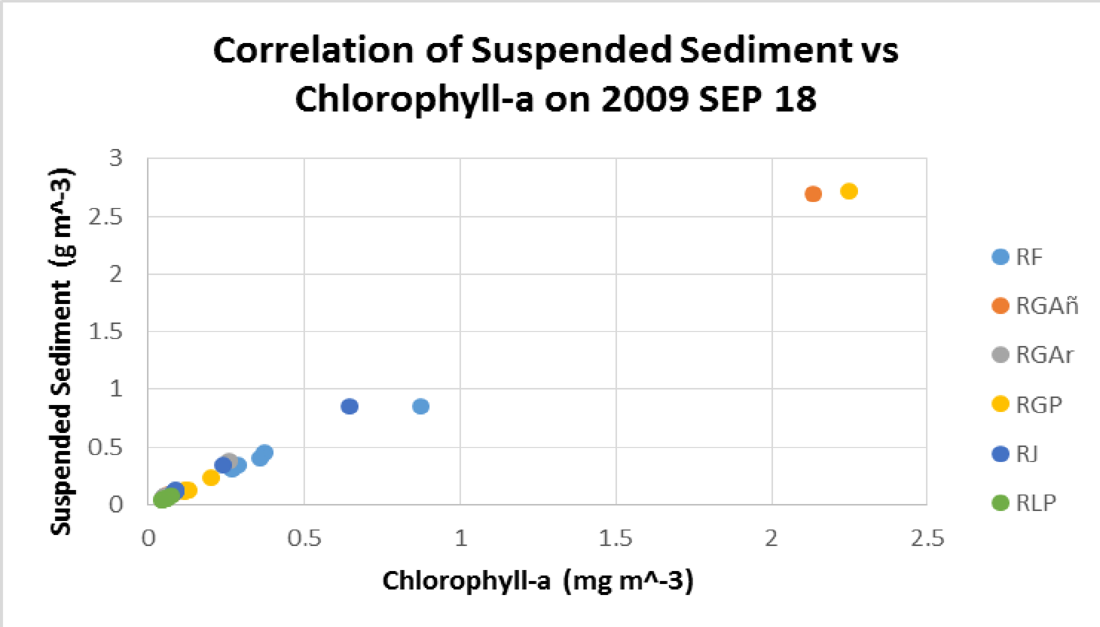
Graph 9:



Graph 10:



Graph 11:



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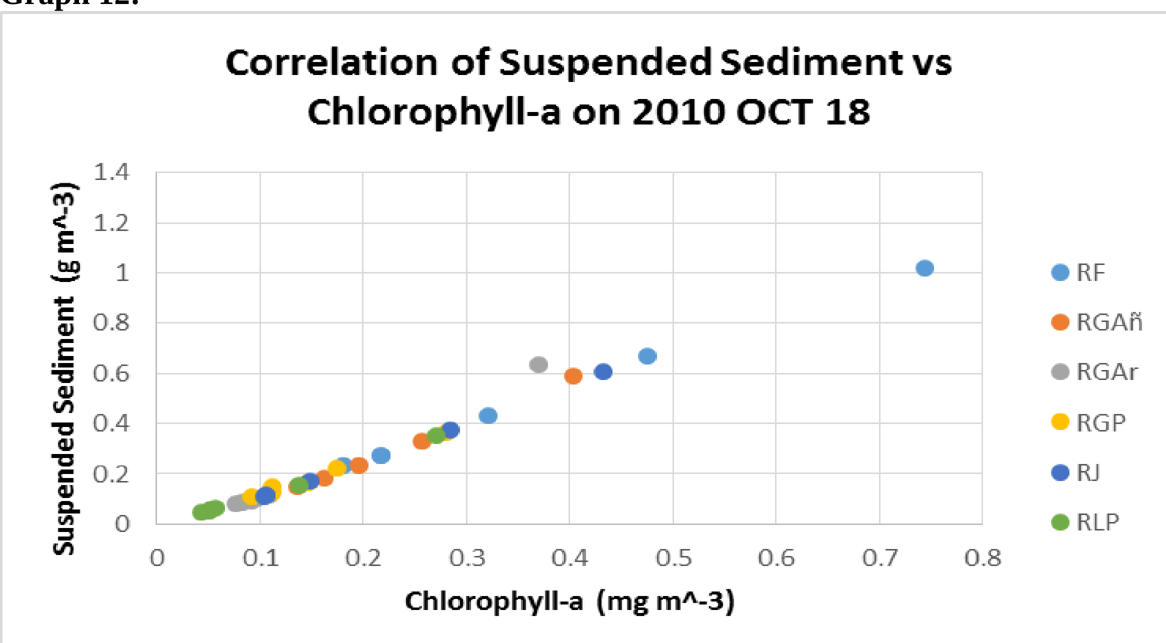
Graph 12:



Graph 7, 8, 9, 10, 11, & 12: Correlation of suspended sediment vs chlorophyll-a of every stream during the 5 strong rainfall events and the event with almost none precipitation (2009 FEB 4).

Tables

Table 1. Location and GPS coordinates of the mouth river..

Stream	Location	GPS Coordinates
Río Grande de Añasco	West	(18.266007, -67.188817)
Río La Plata	North	(18.475475, -66.254453)
Río Jacaguas	South	(17.974300, -66.539842)
Río Grande de Patillas	South	(17.979625, -66.016892)
Río Grande de Arecibo	North	(18.472761, -66.710607)
Río Fajardo	East	(18.328218, -65.627234)

Table 2. Statistical Analysis of Variance (ANOVA) between rivers of the five rainfall events and the no precipitation event was done, the table shows if the analysis has significance or no significance.

STATISTICAL ANALYSIS BETWEEN RIVERS

Date of Precipitation		*Significance*	*No significance*
2007 NOV 23			
	Suspended Sediment	x	
	Chlorophyll-a	x	
2008 OCT 19			
	Suspended Sediment	x	
	Chlorophyll-a	x	
2009 FEB 4			
	Suspended Sediment	x	
	Chlorophyll-a	x	
2009 NOV 17			
	Suspended Sediment	x	
	Chlorophyll-a	x	
2009 SEP 18			
	Suspended Sediment	x	
	Chlorophyll-a	x	
2010 OCT 18			
	Suspended Sediment	x	
	Chlorophyll-a	x	

Table 3. Statistical Analysis of Variance (ANOVA) between the five rainfall events and the no precipitation event of every river was done, the table shows if the analysis has significance or no significance.

STATISTICAL ANALYSIS BETWEEN RAINFALL EVENTS

Rivers	*Suspended Sediment*		*Chlorophyll-a*	
	Significance	*No Significance*	*Significance*	*No Significance*
Río Fajardo (RF)		x		x
Río Grande de Añasco (RGAñ)	x		x	
Río Grande de Arecibo (RGAr)	x		x	
Río Grande de Patillas (RGP)	x		x	
Río Jacaguas (RJ)	x		x	
Río La Plata (RLP)		x	x	