Final Report to UPR-Sea Grant

Application of the Soil and Water Assessment Tool (SWAT) to Estimate Discharge and Sediment Yields from the Río Grande de Añasco Watershed, Puerto Rico

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I. Problem Statement

FROM RIDGES TO REEFS-LAND USE AND SEDIMENT YIELDS AS CORAL REEF STRESSORS

Localized increases in anthropogenic stresses are considered as an important cause of the decline in living coral cover observed throughout the Caribbean (Gardner et al., 2003; Mora, 2007). Estimates suggest that two-thirds of the 26,000 km^2 of coral reefs in the Caribbean are at risk from at least one source of anthropogenic threat, and approximately one-third are perceived to be threatened by coastal development (Burke and Maidens, 2004). Excess delivery of land-based sediments exerts an important control on the condition of coral reefs. High sediment concentration in the water column reduces the amount of light needed for photosynthesis by symbiotic algae, while settling of sediment can smother existing coral or reduce the surface area suitable for new growth (Hubbard, 1986; Rogers, 1990; Fabricius, 2005; Erftemeijer et al., 2012).

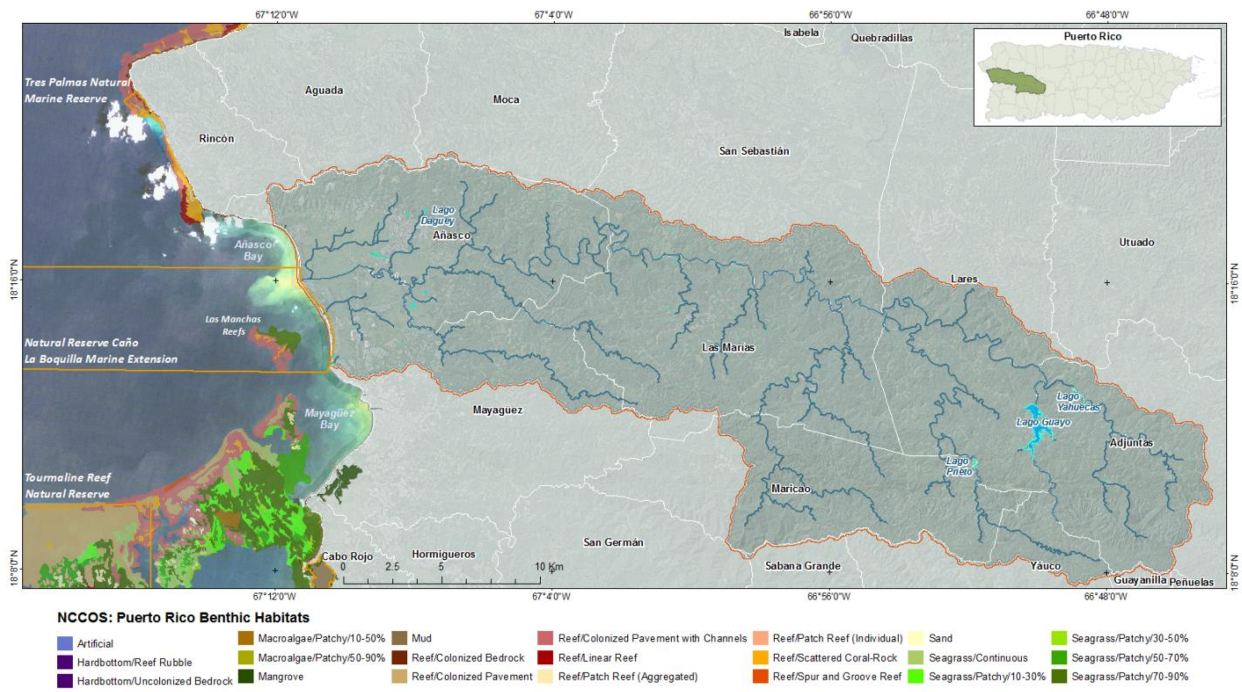


Figure 1. *RGA watershed and marine coral reef communities location map, within the context of Añasco and Mayagüez Bays and eight municipalities intersecting the RGA watershed boundary.*

Coral reefs in the Commonwealth of Puerto Rico (PR) are among the most highly threatened of the entire Caribbean Region (Burke and Maidens, 2004), and pollution from land sources of contamination ranks high as a priority threat together with increased surface seawater temperatures, a higher incidence of disease, and overfishing (Ballantine et al. 2008; Hernández et al., 2012). Community partners, NOAA, and the Department of Natural and Environmental Resources have recommended that reducing land-based pollution and improving education are key actions needed to reduce the threats to coral reefs (Commonwealth of PR and NOAA, 2010), and these recommendations have been integrated into the PR Local Action Strategy Plan (Commonwealth of Puerto Rico and NOAA, 2011). This project addressed these actions by following a modeling-based approach to quantify hydrologic and surface erosion processes within the Río Grande de Añasco (RGA) Basin (Figure 1) and by quantifying sediment delivery and plume dynamics within the Añasco-Mayagüez Bay (AM).

Evidence from AM Bay indicates that its poor water quality, low living coral cover, and abundance of terrigenous sediments are all associated with high sediment yield rates originating from inland sources (Morelock et al., 1983). Previous sedimentation and reef ecosystem studies have shown that AM Bay is highly impacted by past and current high sediment loading rates. Some of the observations supporting these assertions include: (a) large areas covered by fine-grained terrigenous sediments; (b) high depositional rates (>10 mg cm^{-2} day^{-1}); (c) high turbidity and low visibility (< 2 m); (d) reef composition dominated by sediment-tolerant species; and (e) low living coral cover (1-17%) (Morelock et al., 1983, 2001; García-Sais et al., 2005) that have displayed signs of decline throughout the first decade of the 21st century (Figure 2). The Manchas North reef close to the outlet of RGA into the AM Bay (Figure 1) appears to be particularly impacted, as both fine sediment and algal turf has been encroaching into surfaces covered with an already low living coral cover (< 5%) (Morelock et al., 2001).

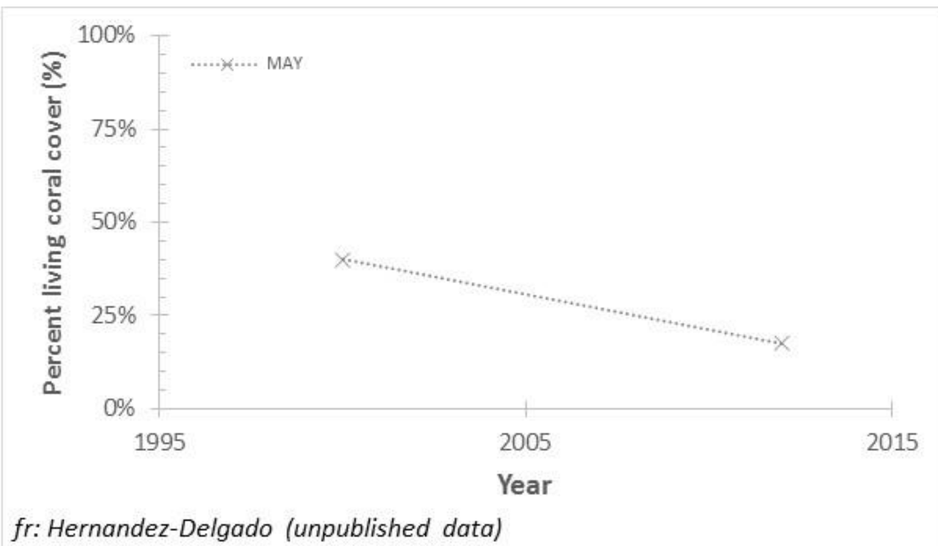


Figure 2. *Living coral cover for a pair of reef sites within AM Bay.*

Maximum sediment yield rates into Puerto Rico's insular shelf are presumed to have occurred during its peak agricultural era (1900's-1950's) (Clark and Wilcock, 2000; Ryan et al., 2008; Ramos-Scharrón et al., in prep.). During this period, only 6-20% of the island's landmass remained as undisturbed forest (Birdsey and Weaver, 1987) and between 32-72% was under active cultivation

(US Agricultural Census Data; Ramos-Scharrón et al., in prep.). Post-agricultural land use patterns induced an island-wide increase in forest cover that increased to 34% in 1985 (Grau et al., 2003). Forests already encompassed 52% of the island's surface area by 2000. Nevertheless, sediment yields are assumed to have remained relatively high due to the effects of mass wasting processes, more limited but still relevant agricultural activity, and remobilization of agricultural-era sediment stored along stream channels (Clark and Wilcock, 2000; Larsen and Santiago-Román, 2000; Larsen and Webb, 2009; Larsen, 2012). In addition, the contribution from more contemporary activities (e.g., urban development) appears to be substantial (Gellis et al., 2006; Ramos-Scharrón, 2010; Gellis, 2012). Recent estimates suggest that basins draining into the west coast of PR have a disproportionately high sediment contribution to the insular shelf relative to other regions. Even though western basins represented only 16% of the total area included in the calculations, a sediment yield estimate of 960,000 metric tons of sediment per year (1200 tons km^{-2} yr^{-1}) for this region equals slightly more than a third (35%) of the yields for the entire island (Warne et al., 2005).

CHARACTERIZATION OF SEDIMENT PLUMES

Previous efforts conducted by the Geological and Environmental Remote Sensing (GERS) Lab have been made for estimating suspended sediments in AM Bay using the Moderate-Resolution Imaging Spectrometer (MODIS) images. However, the temporal availability of these images is very limited due to the typical large cloud coverage of the area. Since a large amount of satellite images are needed for algorithm development and remote sensing monitoring, the GERS Lab, in collaboration with CariCOOS, obtained European Space Agency (ESA) data from the Medium Resolution Imaging Spectrometer (MERIS). This sensor has 300 meters of spatial resolution and 15 bands from VIS to NIR that can be selected depending on the application. ESA has also developed a specific algorithm for suspended sediments that can be easily applied using the BEAM software. MERIS was launched on board of the ESA ENVISAT in March 2002 and ceased operations in May 2012. However, this timeframe served well for our study interests. This project has combined image processing and GIS techniques for the spatial and temporal analysis of the RGA sediment plume in AM bay and the relationship with its basin. The developed procedures will facilitate the monitoring of rivers discharge and its impact to coastal environments elsewhere.

RÍO GRANDE DE AÑASCO WATERSHED

The RGA basin is the largest basin draining towards the western coast of Puerto Rico and is the fourth largest drainage area on the island. The basin covers at least some portions of eight different municipalities (i.e., Añasco, Mayaguez, San Sebastián, Las Marías, Maricao, Lares, Yauco, and Adjuntas; Figure 1). The 467 km^2 watershed occupies 30% of the 1570 km^2 of land area flowing to the west coast of PR, and is consequently responsible for a large share of the sediment and contaminants delivered to these coastal waters. Average annual runoff rates equal 1170 mm yr^{-1} (546.4×10^6 m^3 yr^{-1}) and this amounts to half of the total of $1{,}108 \times 10^6$ m^3 yr^{-1} of runoff delivered to the western coast of Puerto Rico from the other two major watersheds in this area (Río

Culebrinas at 389 x 10^6 m^3 yr^{-1} & Río Guanajibo at 172 x 10^6 m^3 yr^{-1}; taken from Larsen and Webb, 2009). Annual suspended sediment loads for RGA have been estimated at 2,669 Mg km^2 yr^{-1} (calculated for this study using discharge data and a sediment rating curve), but these are based on a very sporadic water-sampling effort (n = 120 samples obtained between February 1968 and April 1995). In addition, these samples were collected at a location representing an area roughly equal to 54% of the entire watershed. Analyses of reservoir sedimentation surveys completed in Lago Yahuecas, Lago Guayo, and Lago Prieto, all of which are located at the headwaters of RGA, resulted in high sediment yield estimates of 760, 860, and 900 Mg km^{-2} yr^{-1} (Soler-López et al., 1998; Soler-López, 1999; Soler-López and Webb, 1999). These rates further support the speculation that this basin exports large quantities of sediment into the Añasco-Mayaguez Bay. Land cover within the headwater portions of the basin is currently dominated by secondary forests with some urban zones and coffee-citrus-plantain croplands in the upper watershed. Meanwhile, the lower areas in the proximity of the main floodplain are within agricultural and pasture uses with minimal forest cover (Corvera-Gommringer, 2005). Mean annual rainfall is estimated to range between 1750 mm in the lowlands to 2500 mm in the highlands. Soils within the basin predominantly have clayey or clayey-loam textures.

Literature reviews reveal that no previous sediment budgeting studies have been conducted for the RGA basin. A sediment budget represents an accounting of the sources and disposition of sediment as it is eroded from its point of origin to its exportation from a basin (Reid and Dunne, 1996), and it provides a methodological and modeling framework to quantify the net and relative contributions from a diverse group of sediment sources within a basin. An important issue to consider is that only a fraction of the sediment produced within a basin during a rainfall event is exported by stormflow generated by the individual event (de Vente and Poesen, 2005). This occurs because sediment yield is the net result of complex processes controlling the rate of sediment production and remobilization, the connectivity of sediment sources with the fluvial network, and the capacity of the stream to transport/store this sediment (Walling, 1983; Parsons, 2011). The combination of remote sensing and GIS model application described here will estimate sediment yield rates from only surface erosion and fluvial sediment transport, while disregarding other potentially important processes such as streambank erosion (Álvarez, 2005), mass wasting (Larsen, 1998), and floodplain/wetland sedimentation.

Project Objectives

The overall objectives of this project were to quantify runoff and sediment yields from the RGA watershed and to characterize the behavior of sediment plumes originating from RGA once they entered the Añasco-Mayaguez (AM) Bay. This project has focused on the following three goals:

1) Apply the SWAT model to estimate runoff and sediment yields from the RGA watershed between 1998 and 2012;

2) Validate and test model results by comparing them to existing runoff and sediment yield data; and

3) Understand how watershed dynamics control the size, spatial distribution, and optical parameters of sediment plumes coming off the RGA outlet into AM Bay as determined from remotely sensed data.

In addition to estimating both runoff and sediment yields into AM Bay, application of the SWAT model has also provided a means to locate important sediment source areas within the RGA watershed. The results of this spatially-explicit water and sediment budget model can help land managers assess various hillslope erosion mitigation strategies to protect both freshwater and marine water resources (Lu et al., 2004). Therefore, the results of this study may be used as an initial step in the development of an erosion mitigation strategy for RGA. These results not only can provide essential input to fulfill the National Water Quality Initiative of the NRCS for the RGA watershed (*www.nrcs.usda.gov/wps/portal*), but may also serve as an aid to achieve the government's public policy water resources goals for Puerto Rico (ELA, 2008; Commonwealth of PR and NOAA, 2010). In addition, the study directly addresses the '*Sustainable Coastal Development*' research theme of the Sea Grant program. The project also indirectly address the '*Ecosystem and ecology*' and the '*Coastal processes*' themes by providing information on the land-based freshwater and sediment inputs that are threatening the marine environment of Puerto Rico.

II. Methods used

<u>SWAT MODEL-DATABASE DEVELOPMENT</u>

A main objective of this project is to apply the Soil and Water Assessment Tool model (SWAT) to the Río Grande de Añasco (RGA) watershed to estimate basin-scale runoff and sediment exportation rates. As represented by Figure 3, SWAT requires various input databases and the process of obtaining, editing, and generating these is described below.

- <u>*DEM*</u> Topographic data is one of the key physically-based inputs required in SWAT modeling for watershed physical partition into sub-basins, channel morphology, and definition of routing reaches and topographic flow paths. The Digital Elevation Model (DEM) used was generated by the Centro de Recaudación de Ingresos Municipales (CRIM) Office of Management and Budget. The original DEM was photometrically derived over USGS Quadrangles (1996-1998) at a fixed spatial cell size of 10 meters, with an estimated vertical accuracy between 0.5 meters, which was considered appropriate for the size of the RGA watershed (Figure 4).

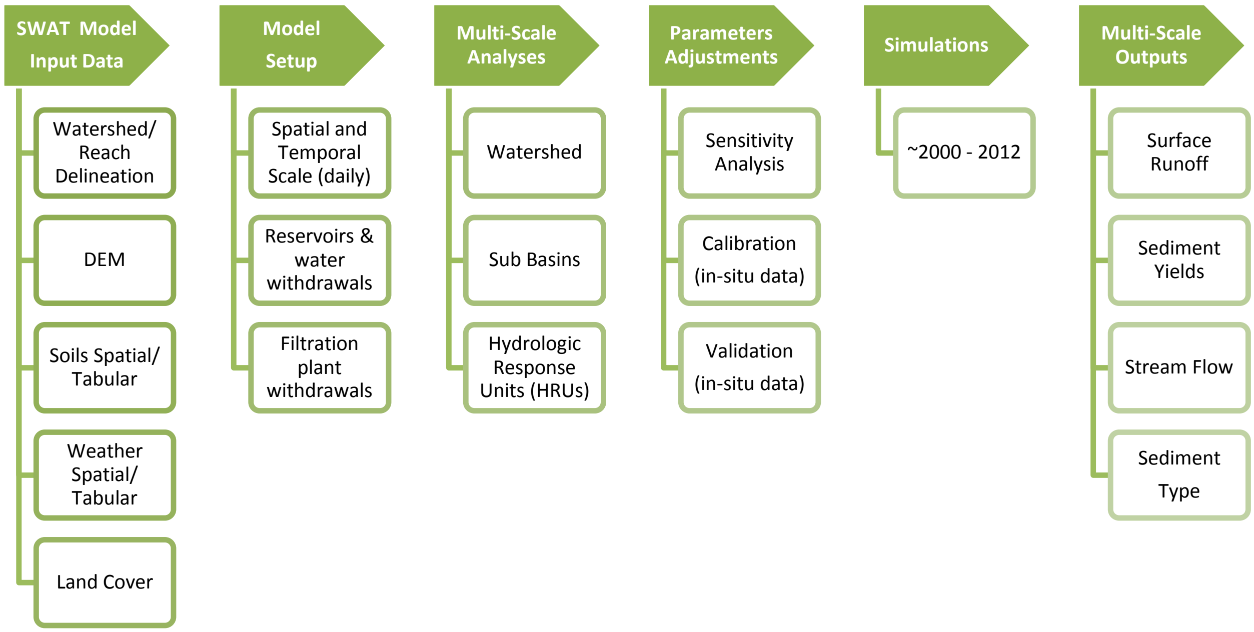


__Figure 3.__ Generalized SWAT Model Flowchart displaying input requirements and products.

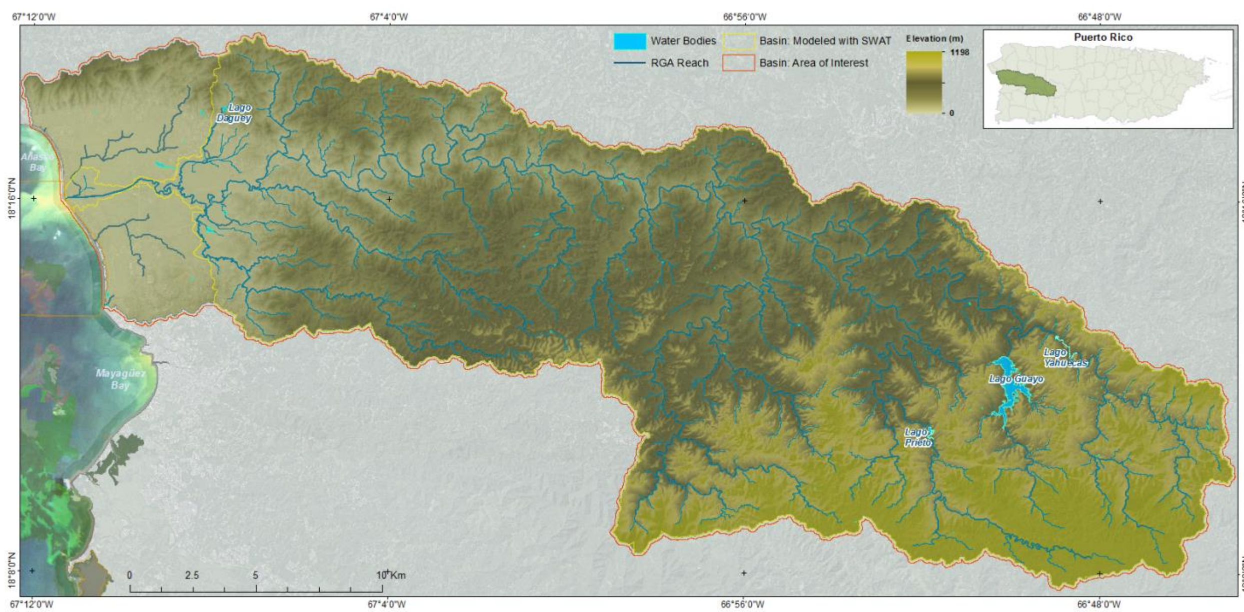


__Figure 4.__ Color-coded representation of the RGA Digital Elevation Model with a drainage network.

- <u>Watershed/River Network</u>- Coastline boundaries and major streams of the RGA watershed were delineated based on a 2010 orthorectified aerial imagery. Watershed boundaries were automatically derived using the Watershed Delineation DEM-base dialog box in ArcSWAT software. The resulting geodatabases were used during the initial steps of the SWAT model as it prepares the model for hydrologic and sediment calculations (Figure 5).

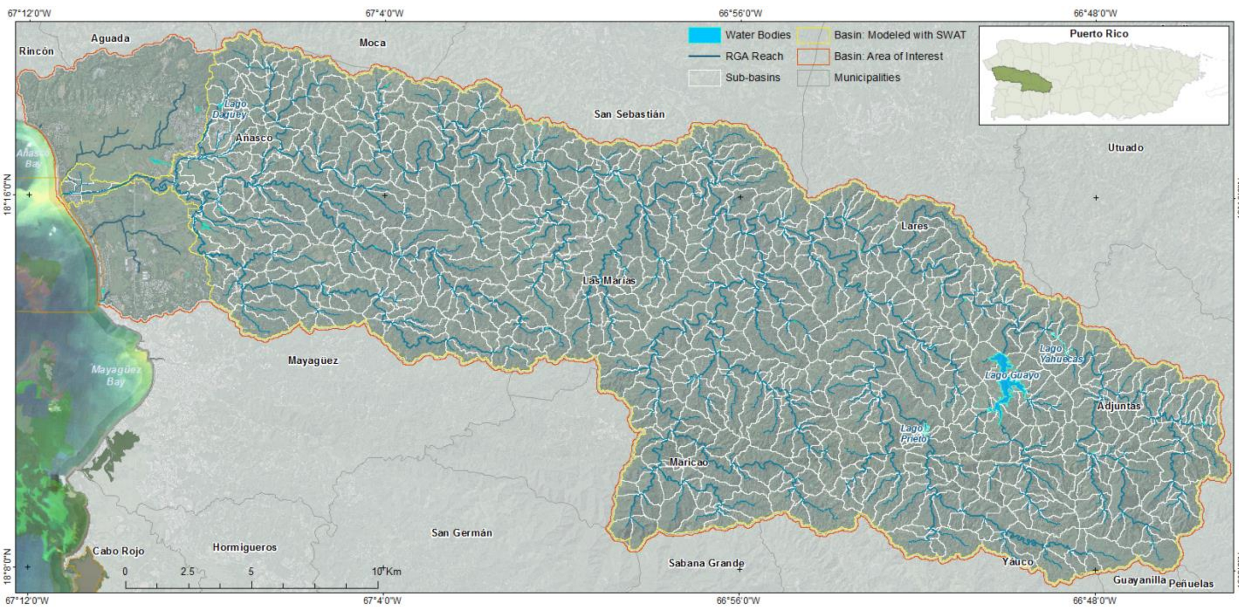


Figure 5. *RGA watershed, stream network, and sub-basins as derived from ArcSWAT watershed DEM-based delineation.*

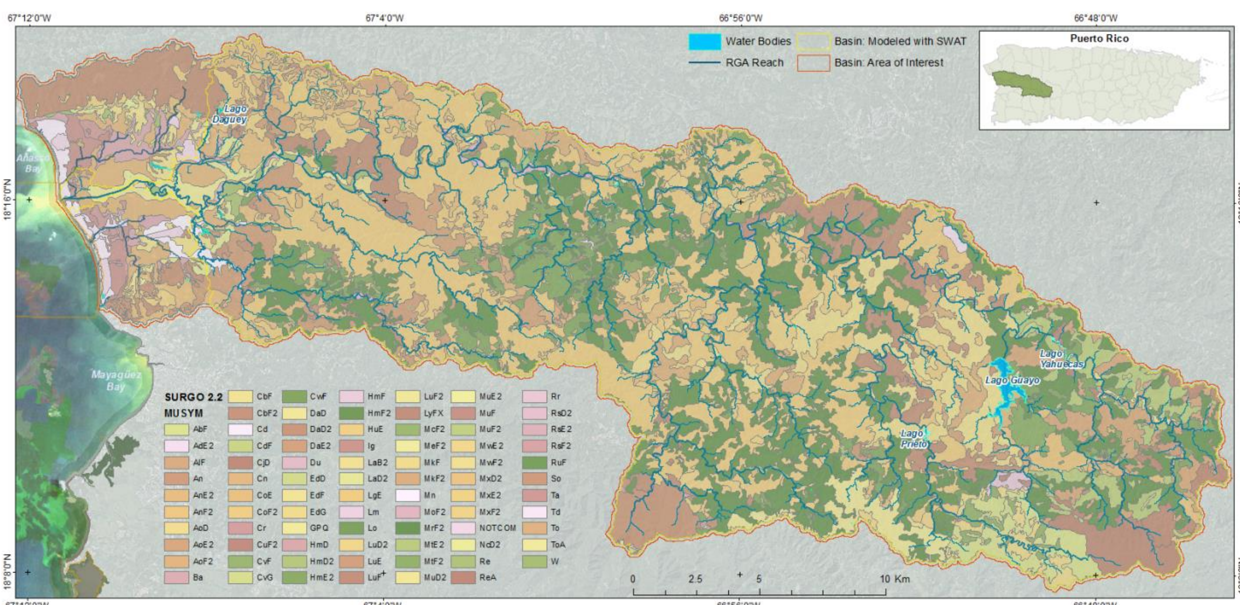


Figure 6. *Soils map of the RGA (SSURGO database).*

- *Soils*- The soils geo-database in the SSURGO shapefile format required by SWAT was obtained from the Natural Resource Conservation Service's Web Soil Survey (NRCS, accessed October 2013). The SSURGO database already includes the soil series types found Puerto Rico and this is compatible with the required inputs for the latest ArcSWAT 2012 software version (Figure 6).

- *Climate data*- Weather data including daily rainfall and maximum and minimum temperatures were obtained from the National Climatic Data Center web page (http://www.ncdc.noaa.gov/cdo-web/). Additional data was obtained from the U.S. Geological Survey Caribbean Water Science Center's webpage (*http://pr.water.usgs.gov/*) or USGS personnel whenever the datasets were not available online. Data was obtained from twelve weather stations located both within and in the immediate periphery of the RGA watershed (Figure 7, Appendix I). Other climate data such as wind speeds, solar radiation, rainfall intensity data required by the model to fill in missing data was mostly unavailable for the twelve weather stations used by our study. ArcSWAT 2012 provides this type of data for two stations in Puerto Rico, both of which are located in the northeast corner of the island. One of these stations represents a 'coastal' setting and the other one represents a 'mountain' setting. Our twelve stations were then categorized into one of these two classes according to their location and the available values were then manually entered based on the already available data.

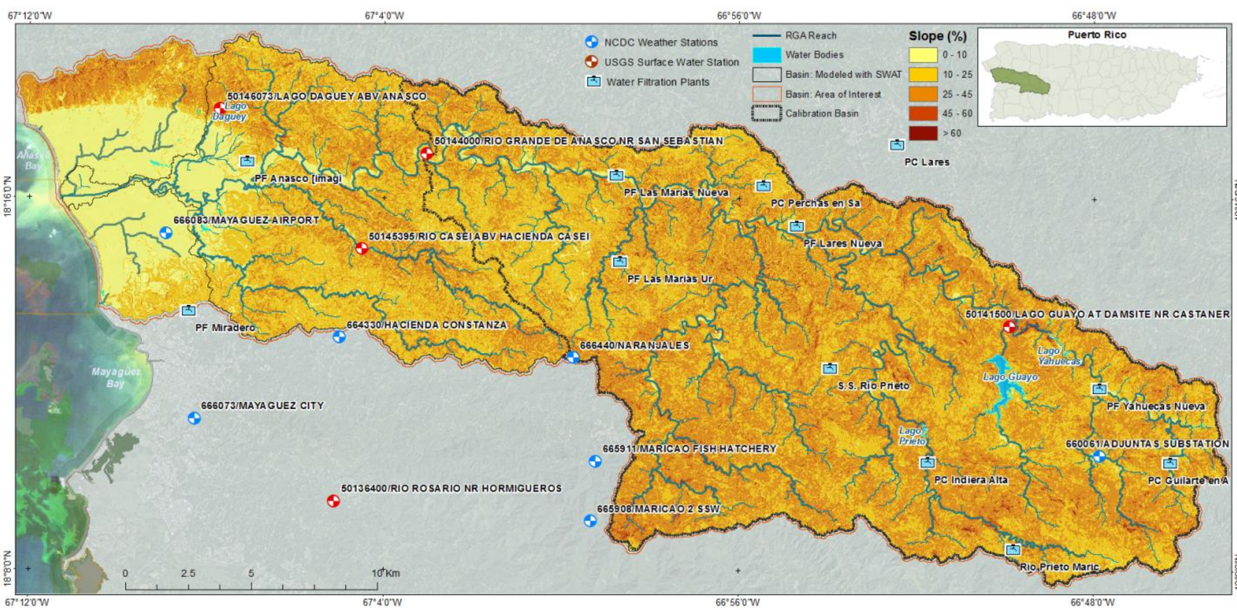


Figure 7. This map depicts the network of NCDC weather stations (daily precipitation and temperature), USGS stream gauges, as well as filtration plants and general slope configuration across the RGA neighborhood.

- *Land Cover*- Land cover categories for the RGA watershed were digitized, at a mapping scale of 1:5000, by means of manual visual interpretation of a Leica ADS40 orthographic image with a 0.3 meter ground sample distance resolution. The source orthoimage was obtained from October 2009 through January 2010 by request of the United States Army Corps of Engineers and made available for this project. The resulting 2010 land cover data layer was partially evaluated through ground-truthing and pre-existing digital maps. The land cover classification scheme was generally based on Anderson et al. (1976) and yielded twenty-nine thematic classes at Level III of the hierarchical classification scheme and seventeen at Level II (see Appendix II). The classification scheme was slightly modified to comply with SWAT model input requirements. Additional details describing the generation of the land cover map are included in Appendix II.

- *Water Reservoirs*- Four main water reservoirs are located within the RGA watershed (Figure 7). Dimensions related to surface area and water holding capacity for these four reservoirs were determined by a combination of reports (Soler-López et al., 1998; Soler-López, 1999; Soler-López and Webb, 1999; Ortiz-Zayas et al., 2004) and aerial imagery analyses. Reservoirs include Lago Daguey, Lago Yahuecas, Lago Guayo, and Lago Prieto. A portion of the water retained by the last three reservoirs just listed is transported through a tunnel to provide water for a hydroelectric plant located outside of the watershed (Central Yauco 1, Autoridad de Energía Eléctrica) and towards Embalse Luchetti in the town of Yauco. This represents a net water loss to the RGA watershed and these losses were estimated here with the aid of personnel from the Autoridad de Energía Electrica (Ing. Jaime López and Ing. Hernán Más). A regression equation that back-calculates the amount of water needed to generate the electrical power reported for the Yauco 1 hydroelectric power plant was used to estimate the total amount of water transferred from all three reservoirs on a monthly basis. This total withdrawal was then partitioned into each of the three reservoirs based on an estimate using their maximum holding water capacities as a reference. Water withdrawals were then subtracted by ArcSWAT from the water held by each of these three reservoirs on a daily time resolution.

- *Water filtration plants*- Water withdrawals from the RGA for domestic use were also included in our analyses. With the aid of personnel from the Autoridad de Acueductos y Alcantarillados we were able to identify twelve water filtration plants that withdraw water from the RGA (Figure 7). Water withdrawals were assigned to each of the sub-basins where the filtration plant appears to be obtaining water from although this was not obvious for several of them.

SWAT Model-Application

Two key processes modeled by SWAT are potential evapotranspiration (PET) and surface runoff. SWAT offers several options for how these two quantities are calculated, but we opted for the default choices. Therefore, PET was calculated based on the Penman-Montheith model (Penman, 1948) and surface runoff was calculated based on the Curve Number method (NRCS, 1986). Total discharge (or streamflow) and total sediment yield at the watershed outlet were modeled at a daily time step between 1-Jan-1995 and 31-Dec-2012. The three first years (1995-1997) were used as a warming up period for SWAT during which the model establishes adequate values of soil moisture, discharge, water held in reservoirs, etc. that provide a baseline from which more reliable estimates are expected. Therefore, values from 1995 through the end of 1997 are not presented here.

SWAT Model Calibration

SWAT requires calibration, which is a process by which parameter values are optimized so that model outputs serve as a better match to observed values. SWAT has an accompanying model called SWAT-CUP meant to facilitate this process. Unfortunately, model calibration still has not been completed for RGA at this time. Our work on this portion of the study will continue as we move forward in generating products for publication. Therefore, all values presented here for discharge and sediment yields are to be considered as *provisional*.

Model calibration for this project relies on stream discharge data collected from a USGS gauging station located on the main RGA channel (USGS 50144000). No calibration attempts were made on sediment yield data due to the low number of samples collected (n = 120) and the sporadic nature of sampling. The streamflow measuring station is located near the municipality of San Sebastián and represents only about 54% of the entire RGA drainage area at its outlet (~468 km^2). The streamflow dataset was obtained from the USGS Caribbean Water Science website (*http://pr.water.usgs.gov/*). Streamflow at this station has been collected since 1963 until the present, while suspended sediment has been collected only sporadically. Discharge data was obtained with a 15-min resolution for the period extending between 1998 and 2012 and was formatted for our purposes (Appendix I). Calibration is intended to be done by comparing model outputs to daily discharge totals for a limited time period (2003-2005). Another time period of equal duration (probably 2008 through 2010) will be used for model validation.

Sediment Plume Analyses

- *Image Pre-Processing*-A total of 307 MERIS images taken between 2005-2011 were downloaded from a web-based archive serviced by ESA's CoastColour Project (*http://www.coastcolour.org/*). Level 1 data (raw images) were processed using the open-source software called BEAM to generate a set of level 2 products, including the concentration of total suspended matter or sediment (TSM or TSS). This parameter was obtained using the MERIS Case 2 Regional Processor, which consist of three different algorithms. The regional algorithm relates the radiances measured by MERIS to the first atmospherically corrected reflectance and then to various water quality constituents. After visual examination of each image, 122 were selected for further analysis based on the availability of corresponding USGS data, and low cloud cover within the study area (Appendix III). These images were georeferenced (WGS 1984) and exported in GeoTiff format to ArcGIS 10.

- *Study Area*- The coastal waters considered for plume analysis were defined based on their proximity to the RGA mouth and the spatial trend and extension of median TSS high values (defined as > 1.8 g m^{-3}) in the 122 MERIS images. First, a polyline layer was created by digitizing 25 km long transects from the RGA mouth at every 15°. Then, TSS values were summarized in a single layer showing each per-cell TSS median value for all of the 122 selected images. This process was completed using the available ArcGIS Cell Statistics tool. After overlaying these two layers (a polyline layer of 25 km and the plumes layer), transects 3 and 8 (Figure 1 in Appendix III) were used to enclose the area, in order to avoid consistent overlaps with the plumes of the neighboring Yaguez and Guanajibo rivers. The extent of the defined area was 492 Km^2 and it covers the northern part of the Mayaguez Bay, 25 km to the west from the coastline and 11 Km to the north of the municipality of Rincón.

- *RGA Discharge Used for Sediment Plume Analyses-* Streamflow data from the USGS RGA station near San Sebastián was used to determine how it was related to the size and spatial distribution of sediment plumes. Data with a 15-min resolution was obtained for the period extending between 1-Jan-1998 and 31-Dec-2012. Gaps in the dataset were filled when these were shorter than approximately 6 hrs and no obvious change in flow rates appeared to have occurred during the period with missing data. All other gaps were noted with a "No Data" label and were highlighted to avoid miscalculation of cumulative discharge values. Streamflow data was used for two purposes. First, it was used to generate a time series of the total cumulative discharge reported for 4, 8, 12, 18, 24, 48 and 72 hours preceding every discharge value between 1-Jan-2000 and 31-Dec-2012 (Appendix III). Therefore, every sediment plume was associated to a series of antecedent discharges ranging from the previous 4-hrs prior to the capture of the image to 72-hrs or three full days before the image was taken. A 3:00 pm local time (AST) stamp was assumed for each image. In order to help characterize each of these values in terms of whether they represent relatively low, moderate or high discharge conditions, we used the 24–hr cumulative discharge total we generated to develop a cumulative discharge-frequency curve (Appendix I). This cumulative frequency distribution curve provided us with a way to describe the matching discharge data in terms of its frequency of occurrence between 1998 and 2012 and to categorize the sediment plumes into those that match low, moderate, or high streamflow conditions.

- *Plume Mapping*-A plume area was estimated for each image using a set of ArcGIS routines in Model Builder. These set of routines start by projecting (State Plane NAD83) and resampling each TSS product into a smaller cell size (5 m). Smaller cell size allows smoother shapes during plume mapping. Next, the reclassification tool executes to generate three classes on each TSS layer based on the criteria defined in Table 2 of Appendix III. The output of this classification is converted to a vector format and clipped-out using the study area as the clip feature. Then, the dissolve routine aggregates all shape elements classified within the same plume category. On this output the area (Km^2) and file name are added into the attribute table. Subsequently, a second output is created by dissolving one more time each layer to create a general plume with only one singular feature per event (Figure 2 in Appendix III). GIS overlay capabilities were used to visualize these outputs and determine river plume tendency and patterns on the selected events. Three analyses were performed using the calculated area (Km^2) for each plume category and the total area of all plumes: (1) a temporal assessment of calculated area; (2) evaluation of the areal extent under three generalized antecedent discharge conditions, and (3) evaluation of the relation between plume area extent and various river discharge parameters by single regression analyses.

- *TSS Spatial Trends*-As an initial evaluation of river plume trends, we used the ArcGIS Cell Statistics tool to calculate the arithmetic TSS mean value for each sediment plume type according to cumulative discharge from RGA. Mean TSS for each plume was categorized into being associated to 'Low Flow', 'Moderate Flow', or 'High Flow'. For this analysis, each of the TSS products was categorized based on the distribution of the 24-hr cumulative discharge values prior to the image stamp time. As described above, the river discharge data used for this categorization was collected at the USGS gauging station #50144000 (RGA near San Sebastián). Three outputs generated from this analysis were standardized for visualization purposes using a single color ramp with 32 TSS categories.

- *Plume Distance/Direction Analysis*-Mean plume length was calculated for 14 transects (Appendix III), using all generalized areas delimited during plume mapping (122 plumes). This approach was completed by clipping out all transects using each plume polygon outline as the clipping feature and measuring the resulting length (Km) for each transect. This procedure was assembled in Model Builder (Appendix III). The resultant layers were then merged, and the attributes were exported into a single Ascii file for further analyses.

- *Spatial Correlation of Sediment Plume Concentration and RGA Discharge* – In an attempt to characterize which areas within AM Bay showed a stronger correlation between TSS and RGA cumulative discharge we conducted the following analyses. Our approach involved calculating individual correlation coefficients between TSS and four different RGA discharge parameters. In order to do perform these analyses we developed a point layer based on a series of 14 lines that radiated from the main RGA outlet. An editing option named Construct Points was used to develop a new point shapefile along these transect lines at every 1 kilometer beginning from the RGA outlet. The result was then edited to only keep those points located on water. The Extract Multi Values Point tool was used on this point layer to obtain TSS values for all of the 180 cells for all of the 122 sediment plumes. All values were then added to the attribute table. The resultant individual TSS cell values were then added to a spreadsheet containing four different RGA discharge parameters: the 24-hr cumulative discharge (in m^3), the peak discharge during the previous 24 hours (in $m^3 s^{-1}$), the average discharge during the previous 24 hours (in $m^3 s^{-1}$), and the median discharge over the previous 24 hours (in $m^3 s^{-1}$).

III. Results and findings

LAND COVER MAP

The distribution and extent of resulting LC categories is summarized in Table 1, while Figure 8 illustrates the level of map details reached at a 1:5000 mapping scale, compared to other existing digital land use maps generated using automated methods. The LC category FOREST dominated in abundance by encompassing 53% of RGA. Level II LC categories URBAN, RANGE WOODY, RANGE HERBACEOUS and CROPLAND all covered very similar surface areas of 43, 46, 48 and 65 km^2, respectively (Figure 9).

Figure 8: Land cover map near the river valley showing the level of information attained at 1:5000 mapping scale.

Although the MIXED CROPS class incorporates a mixture of BANANA and COFFEE, the COFFEE category was the dominating agricultural class (Figure 9). Intensive URBAN land cover Level III categories are dominated by LOW DENSITY RESIDENTIAL (17 km^2), followed by MED DENSITY RESIDENTIAL with 15 km^2 (Figure 9). Rangeland classes, in the other hand, are dominated by HERBACEOUS vegetation (55 km^2), closely followed by the SHRUB AND BRUSH type with 49 km^2 (Figure 9). Spatially, most HIGH DENSITY RESIDENTIAL areas are located in the valley area closer to the coast or along the main road network. Most PASTURE/HAY/INACTIVE AGRICULTURE areas are also located within the valley, where HAY cultivation is a very common practice. RANGELAND areas, also associated with inactive or abandoned agriculture, are widely spread throughout the mountainous part of the watershed, as well as the LOW DENSITY RESIDENTIAL cover type that presents a similar pattern. From the aerial image it is difficult to determine how much of the RANGELAND areas are actually being used for grazing.

Resulting land cover digital maps (Figure 10 and 11) are available as full resolution ArcGIS shapefiles. The raster format product has been prepared in accordance to the SWAT model requirements, with geographic projection referred to State Plane Puerto Rico / US Virgin Islands (Zone 5200), NAD 83, GRS 80, units-meters.

Table 1: RGA classification scheme and resulting land cover area and percentage breakdown

LAND COVER I	LAND COVER II	LAND COVER III	Level II Area (km²)	Level II % Total	Level III Area (km²)	Level III % Total
1 Urban or built-up or Developed	11 Residential	111 High Density Residential			7.78	1.46
		112 Medium Density Residential			14.83	2.78
		113 Low Density Residential			17.46	3.27
	14 Transportation, communications, utilities	140 Transportation			0.80	0.15
	15 Commercial and/or Industrial Complexes	150 Comercial/Industrial Complexes	43.05	8.07	2.17	0.41
	19 Open Space/Transitional/Artificially Barren	193 Barren/Transitional Land			0.63	0.12
		194 Land Fill			0.30	0.06
		195 Gravel Pit	1.55	0.29	0.62	0.12
2 Cultivated Land	21 Pasture	212 Hay / Pastures / Inactive Agriculture			20.58	3.86
		213 Grassland	21.27	3.99	0.73	0.14
	22 Cropland / Agriculture	220 General Agriculture			3.18	0.60
		221 Coffee			23.22	4.35
		222 Banana/Plantain			14.87	2.79
		223 Citrus			1.94	0.36
		224 Mixed Croplands			22.05	4.14
	23 Nurseries/Horticulture	230 Nurseries/Horticulture	65.64	12.31	0.34	0.06
3 Rangeland	31 Rangeland/Shrubland	310 Herbaceous Rangeland			48.52	9.10
		312 Shrub and Brush Rangeland			46.33	8.69
	34 Riparian	341 Herbaceous Rangeland			6.55	1.23
		342 Shrub and Brush Rangeland	103.88	19.48	2.45	0.46
4 Forest Land	43 Mixed Forest	430 Mixed Forest: Semideciduous and Evergreen	285.63	53.56	285.63	53.56
5 Water	51 Streams / Canals	510 Streams / Canals			3.86	0.72
	53 Reservoirs / Ponds	530 Reservoir / Ponds			1.33	0.25
	54 Bays / estuaries	540 Bay / Estuaries			0.83	0.16
		541 Aquiculture	6.11	1.15	0.09	0.02
6 Wetlands	61 Estuarine Forested	610 Mangroves	0.36	0.07	0.36	0.07
7 Barren Land	72 Sandy Areas	720 Sandy Areas			0.16	0.03
	74 Exposed Rocks	740 Exposed Rocks			0.04	0.01
	76 Barren Land	760 Transitional Areas	5.78	1.08	5.61	1.05
TOTAL			533.27	100.00	533.27	100.00

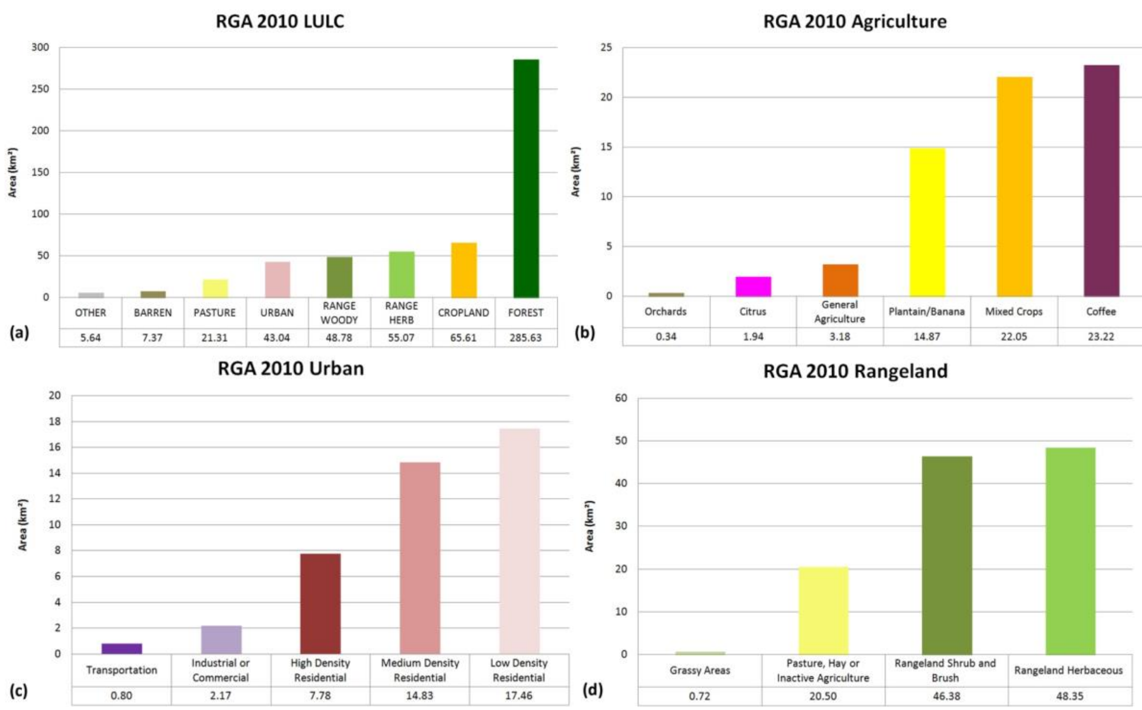


Figure 9: Resulting distribution of Rio Grande de Añasco watershed 2010 land cover categories.

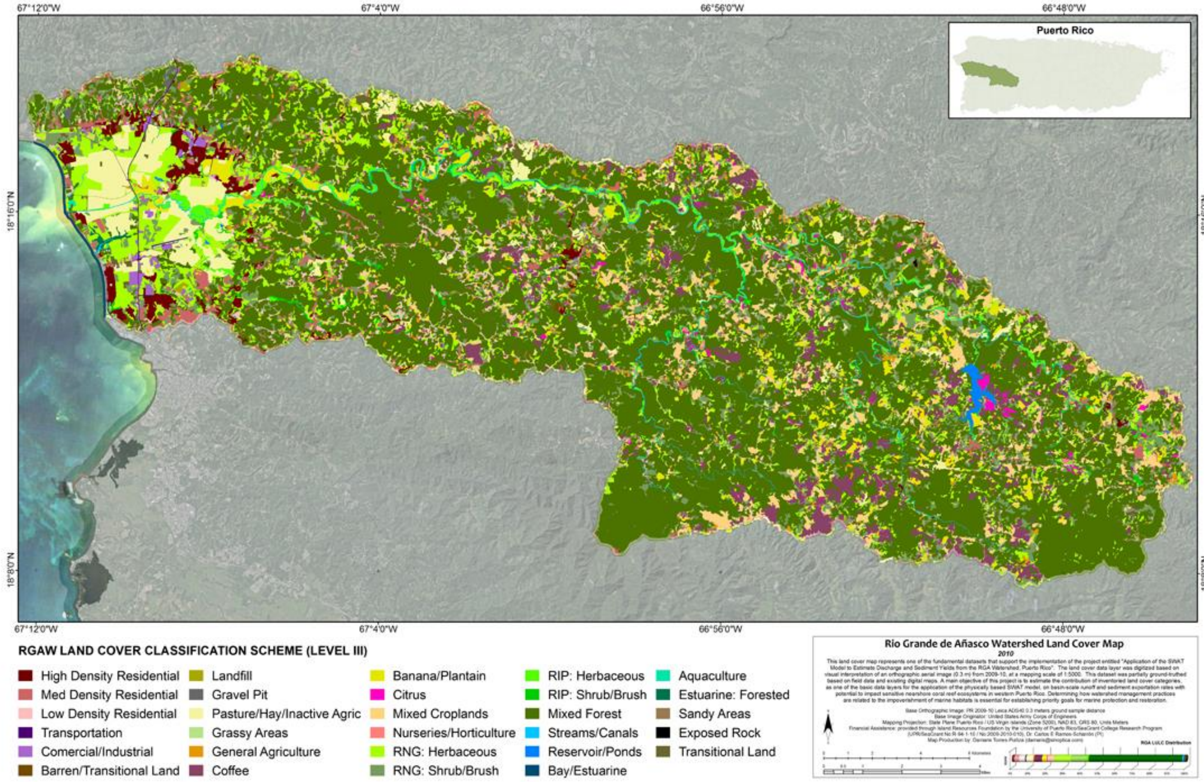


Figure 10. *Land cover map (Level III) of RGA for 2010 created using visual interpretation of an AS40 very high resolution imagery and other land use information.*

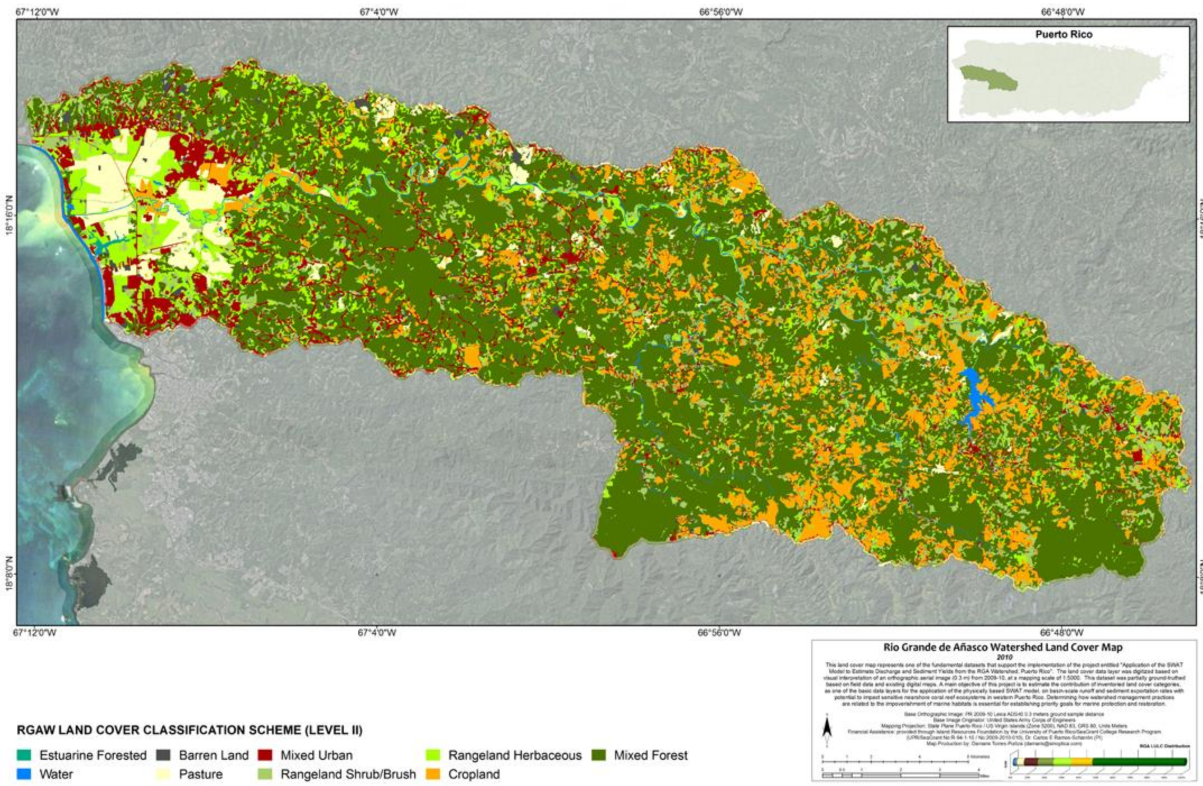


Figure 11. *Land cover map (Level II) of RGA for 2010 created using visual interpretation of an AS40 very high resolution imagery and other land use information.*

SWAT MODEL CALIBRATION

Although model parameter calibration has not been finalized at this time, model results have been compared to observed values to assess the model's ability to predict daily discharge at RGA (Figure 12). SWAT was applied utilizing the location of the USGS streamflow measuring station (RGA near San Sebastián, Figure 7) as the watershed outlet to obtain discharge estimate outputs at that particular location. Results demonstrate that about 50% of the variability in observed daily discharge was accurately estimated by SWAT. This sort of result is typical of SWAT applications and is deemed acceptable for the purposes of this report. Model calibration will be eventually completed for the purposes of writing a pair of articles in scientific journals.

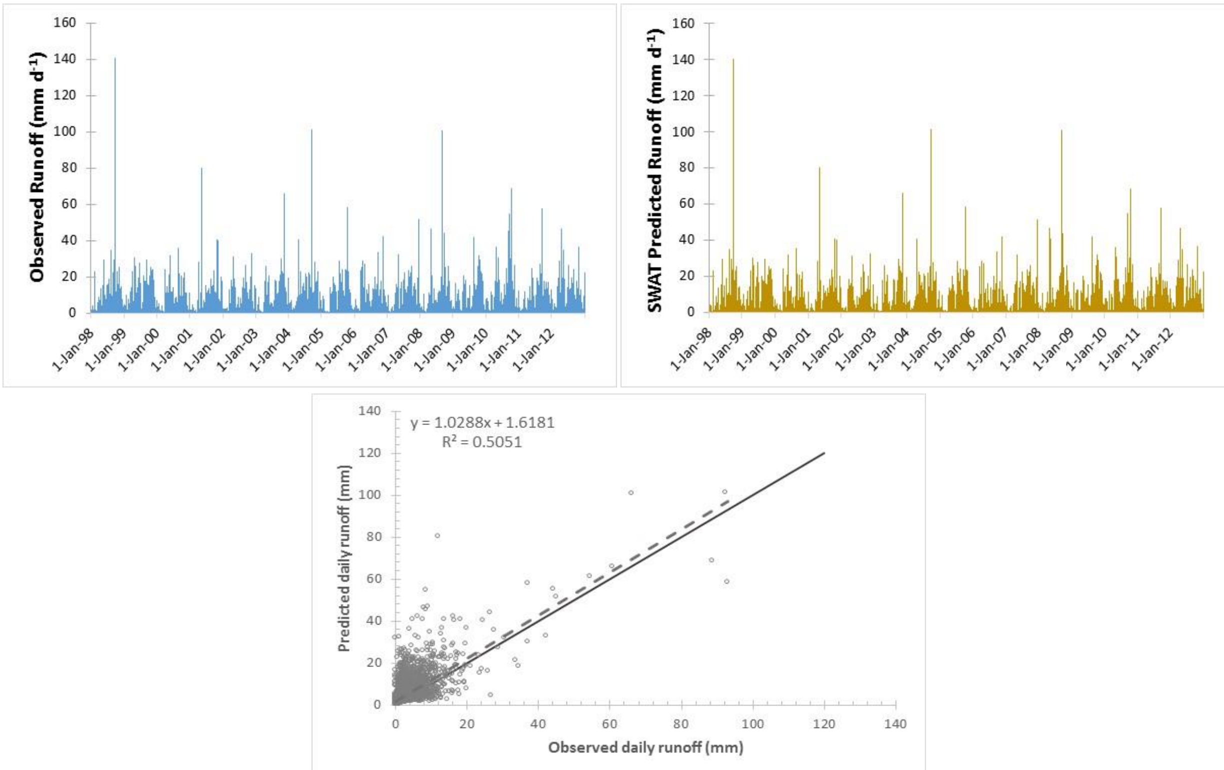


***Figure 12**. (a) Observed daily runoff at USGS RGA near San Sebastián stream gauging station from 1998 through 2012; (b) SWAT-predicted daily runoff for the same location as the RGA stream gauging station; (c) Scatter plot comparing predicted versus observed runoff; the dashed line represents the linear regression resulting from the data and shown as an equation, while the solid line corresponds to a line of perfect correlation.*

SWAT MODEL-WATERSHED SCALE DISCHARGE AND SEDIMENT YIELDS

Daily precipitation averages for the entire RGA between 1-Jan-1998 and 31-Dec-2012 ranged from 0.0 to 126.7 mm (Figure 13). The two events with the highest rainfall rates were registered as a result of Hurricane Georges (113.5 mm on 21-Sep-1998) and Tropical Storm Jeanne (126.7 mm on 15-Sep-2004). Daily runoff estimated by SWAT ranged from 0.1 to 105.4 mm. The two days with the highest discharge rates were 21-Sep-98 with 98.1 mm and 15-Sep-2004 with 105.4 mm. Daily suspended sediment yields estimated by SWAT ranged from 0 Mg to 10,062 Mg of sediment estimated for rainfall associated to Hurricane Georges on 22-Sep-1998 (Figure 13). The second highest daily yield was estimated for rainfall associated to Tropical Storm Jeanne on 15-Sep-2004 and this totaled 9,368 Mg of sediment.

The main components of the water budget considered by SWAT and presented here are water inputs by precipitation and water losses or withdrawals associated to evapotranspirtation (ET), discharge, domestic uses obtained from surface waters at water filtration plants, and that taken from the Yahuecas, Guayo, and Prieto reservoirs and directed towards Embalse Luchetti outside of the RGA watershed. In order to simplify the presentation of estimates for each of these values, we opted to compile data on a monthly basis. Monthly rainfall (averaged for the entire RGA watershed) ranged from 12.6 and 444 mm, while ET and discharge ranged from 19.9 – 88.9 mm and 12.1 – 335 mm, respectively (Figure 14). Monthly water withdrawals by filtration plants ranged only between 4.2 and 4.3 mm, while estimated diversion of water at the three abovementioned reservoirs was steadily 4.0 mm. ET displayed the expected seasonal trends of relatively lower values during the slightly milder temperatures typical of January, February, and December and the higher rates of the warmer late spring, summer, and fall months (Figure 14). Similarly, discharge displayed the expected bimodal distribution of higher flows in the months of April to May when 20% of the annual discharge was delivered during the months of August to October, which were responsible on average for 40% of annual discharge. The model estimated relatively lower flows during January to March, June to August, and November to December.

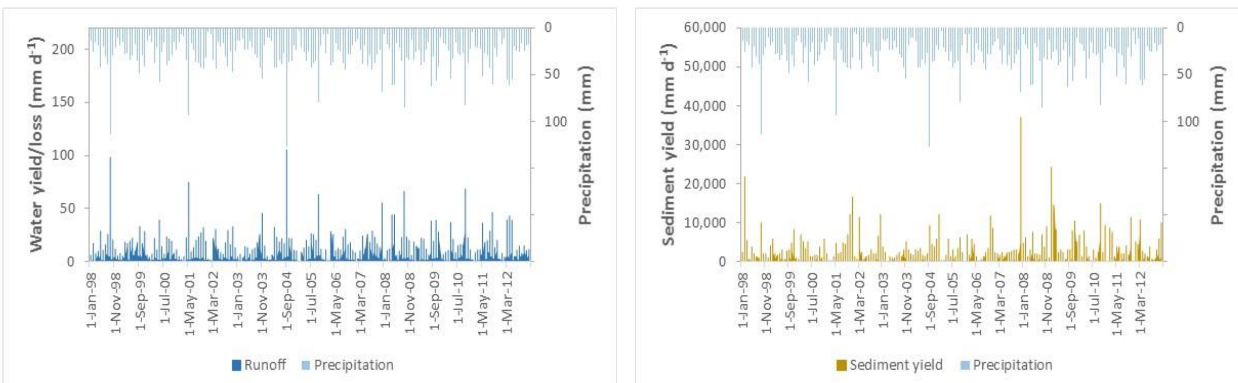


Figure 13. *(a) Daily precipitation and runoff estimated by SWAT between 1-Jan-1998 and 31-Dec-2012; (b) Daily precipitation and suspended sediment yield estimated by SWAT for the study period.*

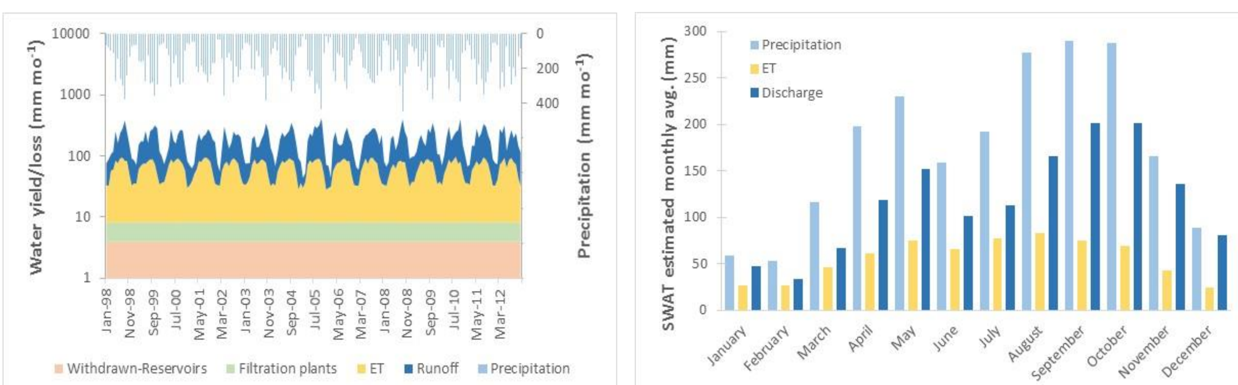
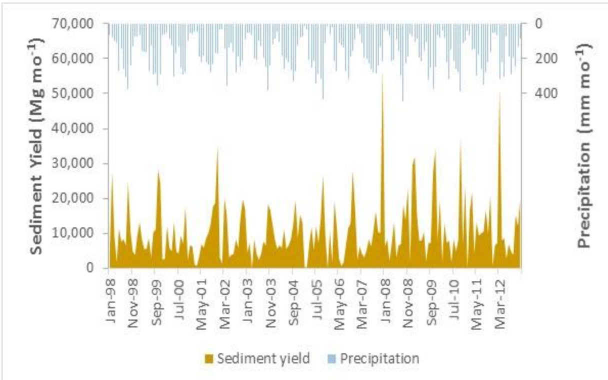


Figure 14. *(a) Monthly precipitation, ET, runoff, and water withdrawals from RGA between Jan-1998 and Dec-2012. (b) Monthly average precipitation, ET, and discharge estimated by SWAT.*

Monthly sediment yields ranged from 0 to 57,248 Mg (Figure 15). The two highest monthly sediment yields were estimated for Nov-2007 (57,248 Mg) and Mar-102 (51,697 Mg). On average, suspended sediment yield was estimated to peak during the months of September through December during which roughly 50% of the annual yield was estimated (Figure 15).



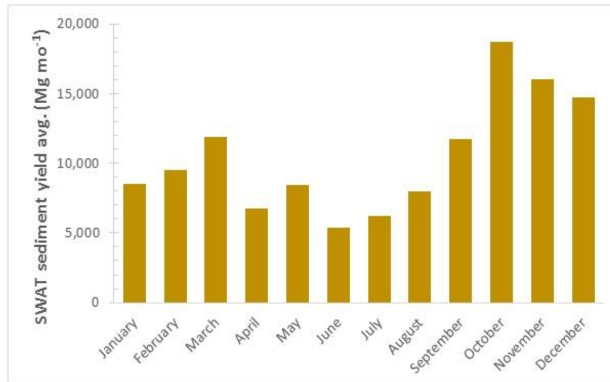


Figure 15. *(a) Monthly precipitation and sediment yields from RGA as estimated by SWAT from Jan-1998 to Dec-2012; (b) Monthly average sediment yields estimated by SWAT.*

Average annual rainfall calculated by SWAT for the entire RGA was **2,118 mm** with values ranging between 1,890 mm (YR 2000) and 2,287 (YR 1999) (Figure 16). Average annual ET was **672 mm**. Annual average discharge was 1,417 mm with values for individual years ranging between 1,222 mm (YR 2000) and 1,602 mm (YR 2005). Overall, SWAT estimated that 65% of the water made available through rainfall got converted into discharge and this is slightly higher than the 57% runoff coefficient value estimated by Larsen and Webb (2009) based on data from the RGA near San Sebastián USGS streamflow station. SWAT also estimated that about 30% of precipitation was lost due to ET, and that water withdrawal by filtration plants and water diversion from the three main reservoirs are each responsible to taking 2% of the total available water (Figure 16).

According to SWAT, average suspended sediment yield from RGA between 1998 and 2012 was 125,854 Mg yr^{-1} with individual annual values ranging from 90,904 (YR 2000) and 189,093 Mg yr^{-1} (YR 2009) (Figure 16). The average sediment yield value translates into an area-normalized value of **270 Mg km^{-2} yr^{-1}** and this is about an order of magnitude lower than those estimated based on discharge data and a sediment rating curve developed from suspended sediment samples collected at RGA (~**2,700 Mg yr^{-1},** this study). This implies that parameter calibration will also have to include those related to the generation of sediment to improve the capacity of SWAT to accurately predict sediment yields.

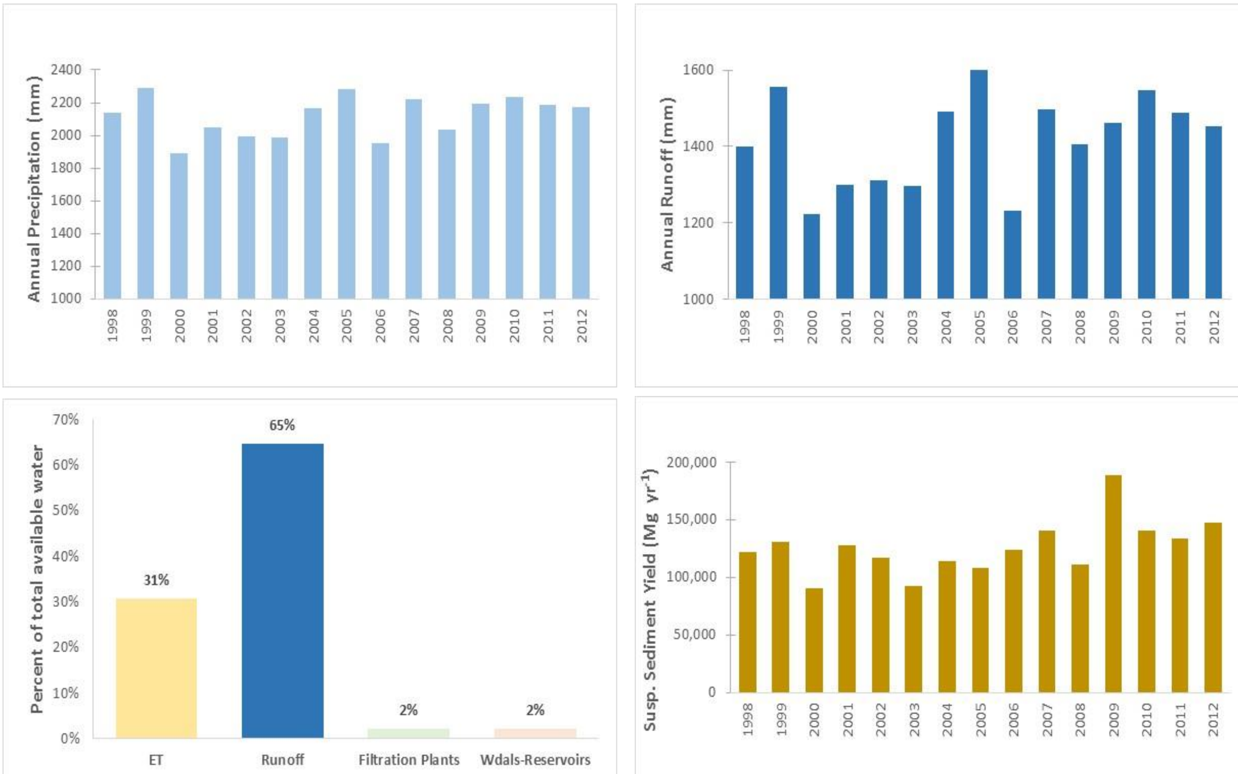


Figure 16. *(a) Average annual precipitation and (b) runoff from RGA as estimated by SWAT between 1998 and 2012; (b) Simplified average water budget for RGA based on SWAT results; (c) Annual suspended sediment yields for RGA as estimated by SWAT between 1998 and 2012.*

SWAT MODEL- COMPARISONS BETWEEN CURRENT CONDITIONS AND A BASELINE REFERENCE STATE

Discharge rates estimated under fully forested conditions were only slightly lower than those estimated based on land cover conditions existing in 2010 (Figure 17). Average annual discharge rates equaled 1,423 mm yr^{-1} between 1998 and 2012, or only slightly higher than those estimated for 2010 land cover conditions, which were estimated as equaling 1,417 mm. In contrast, sediment yield values estimated for fully forested conditions averaged 18,713 Mg yr^{-1} (40 Mg km^{-2} yr^{-1}) and these are almost a full order of magnitude lower than those estimated based on conditions in 2010.

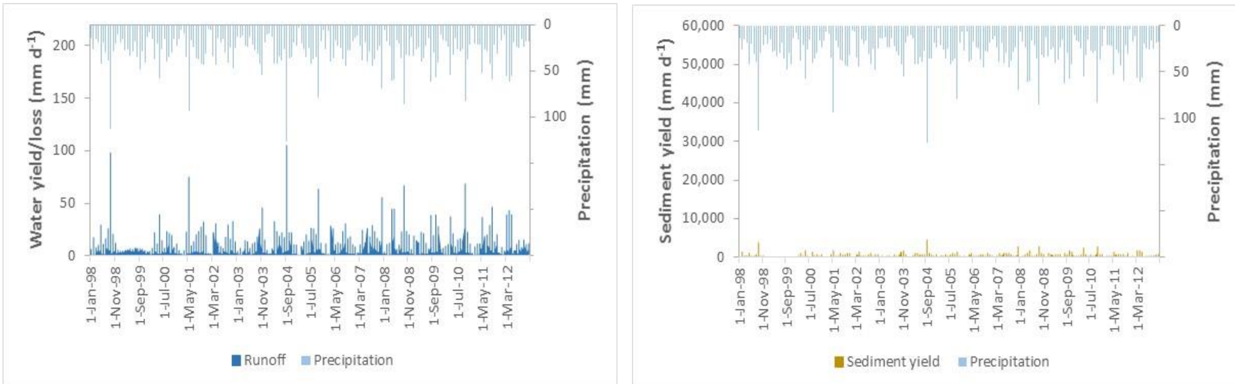


Figure 17. *(a) Daily discharge from RGA estimated by SWAT for rainfall conditions between 1-Jan-1998 and 31-Dec-2012 assuming a fully forested condition; (b) Daily sediment yields estimated by SWAT assuming a fully forested condition.*

SWAT MODEL-SPATIAL DISTRIBUTION OF SEDIMENT SOURCES

The RGA watershed was delineated and subdivided into 801 sub-basins based on surface topography configuration defined by a DEM. Sub-basins were further subdivided into 68,539 Hydrological Response Units (HRUs) based on unique combinations of land use, slope, and soil type. These physically based subunits allow scrutinizing and visualizing, spatially and temporally, the SWAT output values at different levels of detail. Our focus here is on surface runoff and sediment yields. The data outputs are preliminary and pending calibration.

- *HRUs:* Runoff and soil loss are strongly modulated by the hydrologic characteristics of the watershed, including soil type, land use and topography. Yet, isolating the corresponding contribution of each influencing factor is difficult. Analysis of SWAT results at the HRU level allows identifying the influence that these spatially varying conditions have over RGA sediment yield and runoff. Figures 18 and 19 are examples of the types of graphics that can be generated to help quantify the role that different slope, land use and soil categories have on sediment yields from RGA.

  Overall, the percent area cover of the five slope (%) categories within RGA are distributed as 0-10 (5%), 10-25 (15%), 25-45 (41%), 45-60 (23%) and >60 (16%). In other words, with 79% of its area classified with slopes over 25%, RGA is mainly a high-relief watershed. SWAT results indicate that slopes greater than 45% contribute on average 63% of the RGA total sediment yield. After area normalization, this value climbs to 68%, of which 40% of the sediment specifically corresponds to steep slopes greater than 60%. The relative sediment yield contribution for the more gentle slopes (0-25%) represented only 19% after normalization. However, slope gradient seems to have a contrasting effect on runoff compared to that of sediment yield. Although, 69% of the runoff can be associated to slope gradients greater than

25% at a watershed level, following normalization the more gentle slope gradients (0-25%) are responsible for generating 53% of the runoff. In contrast, 47% of the runoff leaving he watershed was generated by steeper slope gradients greater than 25%. This can be attributed in part to the highly permeable urban areas that predominate the lower and flatter portions of RGA. In contrast, SWAT calculated a higher contribution from steeper sections of RGA to sediment yields than more gently sloping areas. This can be in part attributed to the higher erosive energy of overland flow acting on steep hillslopes and to the abundance of bare soils and cropland in the higher and steeper sections of the watershed.

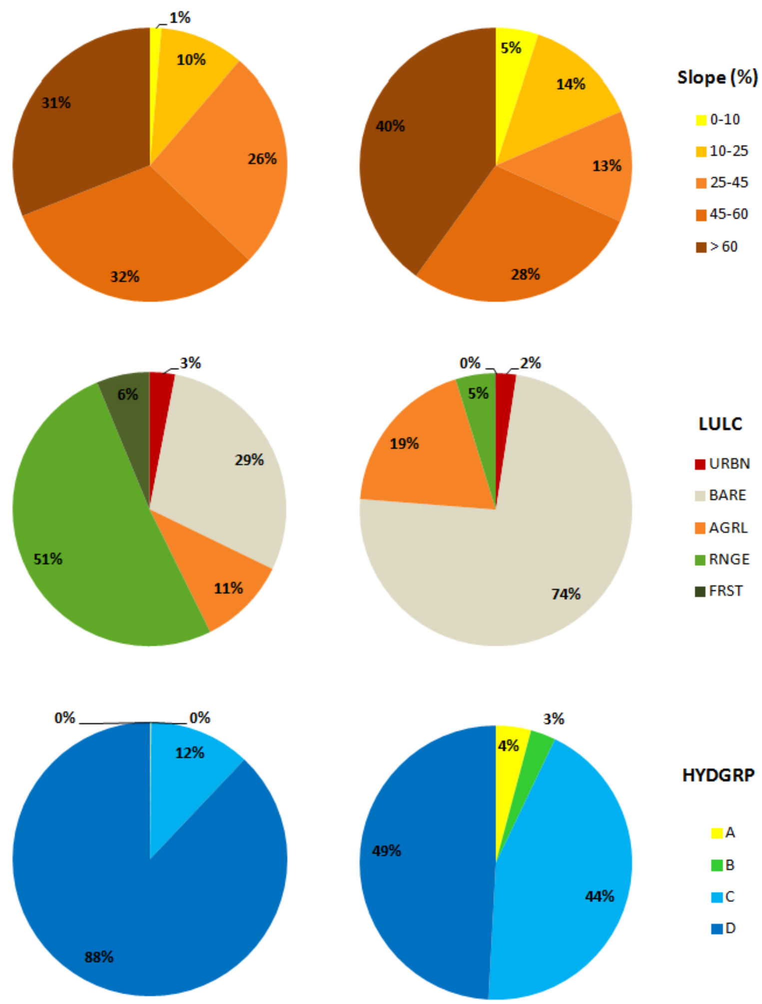


Figure 18. *Average annual Sediment Yield within HRUs for the entire RGA (left) and per unit area (right) of slope type (top), landuse (middle) and hydrologic soil group (bottom) categories (1998 – 2012).*

Overall, HRUs average sediment yield estimates per LULC categories suggest that the rangeland (RNGE) class contributes the larger amount of sediment to the system with 51%, followed by barren (BARE) with 29%. However, area per class normalization allows separating the significance of the class BARE contribution (74%) to sediment outputs, followed by agricultural lands (AGRL) with 19%, then rangeland (5%) and urban (URBN) with 2%. In contrast, runoff associated to LULC classes show a significant 71% contribution from the vegetated classes FRST and RNGE, against a 29% for the more intensely managed classes URBN, BARE, AGRL at a watershed scale. Area normalized runoff values shows a different scenario, in which those more intensely managed classes are the ones which contributed most runoff to the system with a combined amount of 92%, being URBN the more significant (44%), followed by AGRL (33%) and BARE (15%). Before considering other water balance components, vegetated lands seem to only contribute a low 8%. It is relevant to highlight here that, although some LULC changes are expected between 1998 and 2012, a single LULC map of 2010 was considered. Yet, similar runoff and sediment yield trends are expected for consecutive years.

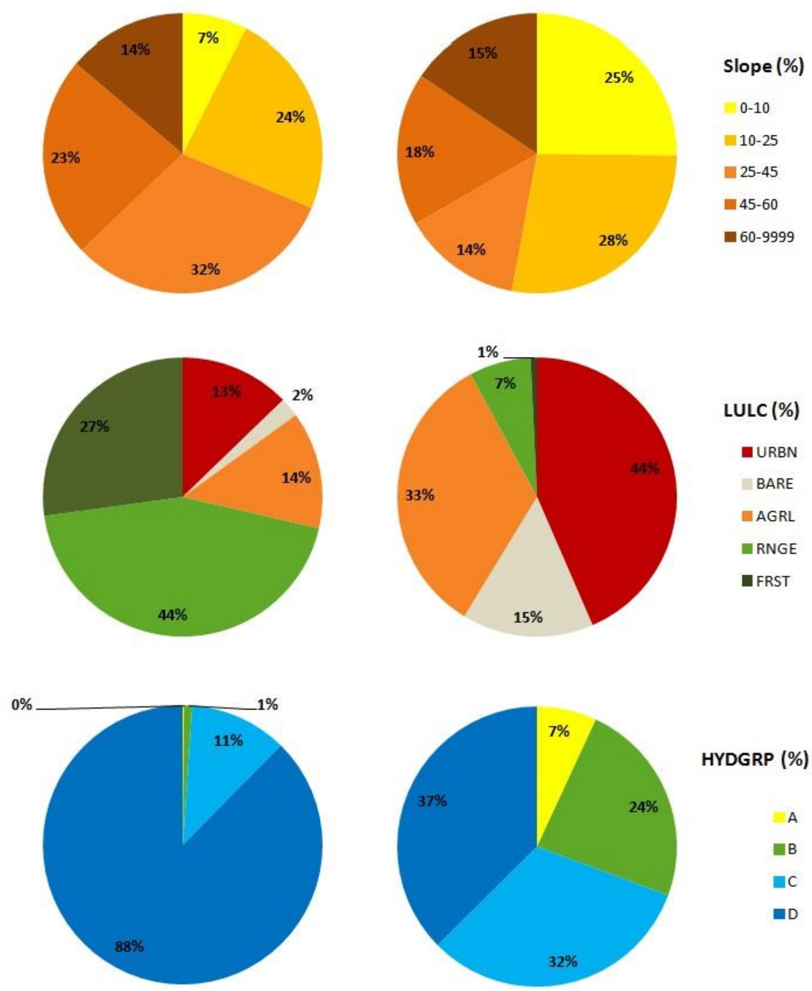


Figure 19. *Average annual Runoff within HRUs for the entire RGA (left) and per unit area (right) of slope type (top), landuse (middle) and hydrologic soil group (bottom) categories (1998 – 2012).*

Eighty soil types are found within RGA (Figure 6). For illustrative simplification, those were categorized by their hydrologic soil group based on SSURGO/NRCS data (link). A significant area (85%) of RGA is classified as high runoff potential - clayed soils (D), and contributes 88% of the sediment to the system, and 13% of the area is classified as the moderately high runoff - moderately fine to fine texture soils (C), and contributes 12% of the sediment yields. Soil groups A (low runoff potential – well-drained sands/gravel) and B (moderately low runoff potential – moderately fine to moderately coarse) are insignificant at watershed scale. After area normalization, soils D still dominates with sediment yields estimates of 49%, closely followed by soils C with 44%, and with only 4% and 3% soils A and B, respectively. Soil group D corresponds to 88% of the surface runoff from RGA. Whereas, after area normalization the proportionality changes to 37%, 32%, 24%, for D, C and B respectively, and a smaller influence from soil group A with 7%. As expected, runoff average values show a clearer correspondence with the hydrologic soil group categories than sediment yield, that is, runoff increases with increasing soil group runoff potential.

The general ranking of HRUs average annual outputs reflect that the top ten high values of sediment yield correspond to the unique combination of BARR – Consumo soil (D) – 60< slope. For runoff the top 10 most influential unique combinations includes BARR - Humatas and Consumo soils (D) – 0-60% slopes. These results are general, but suggest that areas showing such unique combination of factors urge priority in the implementation of Best-Management Practices. Given that BARR – Consumo combination are the common factors for both highest sediment yield and runoff, and given that the FRST class is the only constant and manageable factor within the top ten lowest values for both sediment yield and runoff, reducing the contribution of sediment from barren lands appear as an immediate first step to improve water quality within RGA and the AM Bay.

- *Subbasins/Reach:* Analysis at subbasin level allows for a more comprehensive visualization and understanding of the spatial and temporal distribution of simulated water and sediment outputs. Figure 20 displays the spatial distribution of average annual sediment yield per sub-basin and reach sediment outflow for the year 2010 (refer to Appendix II for visualization of spatial and temporal monthly distributions). Similar to the HRUs analysis, by assessing the source sub-basin with the higher (sub-basin 12) and lower (sub-basin 781) sediment yield outputs is also apparent the correspondence between FRST (97%) cover and lower values of soil loss at sub-basin and reach level. Reach sediment outflow values in Figure 20 also illustrate how the reduced FRST cover and abundance of BARR land cover affect the water quality of the tributary associated to sub-basin 12. Visualization allows identifying areas of relative high contribution of sediment to inform decision-making and achieve river conservation and management targets.

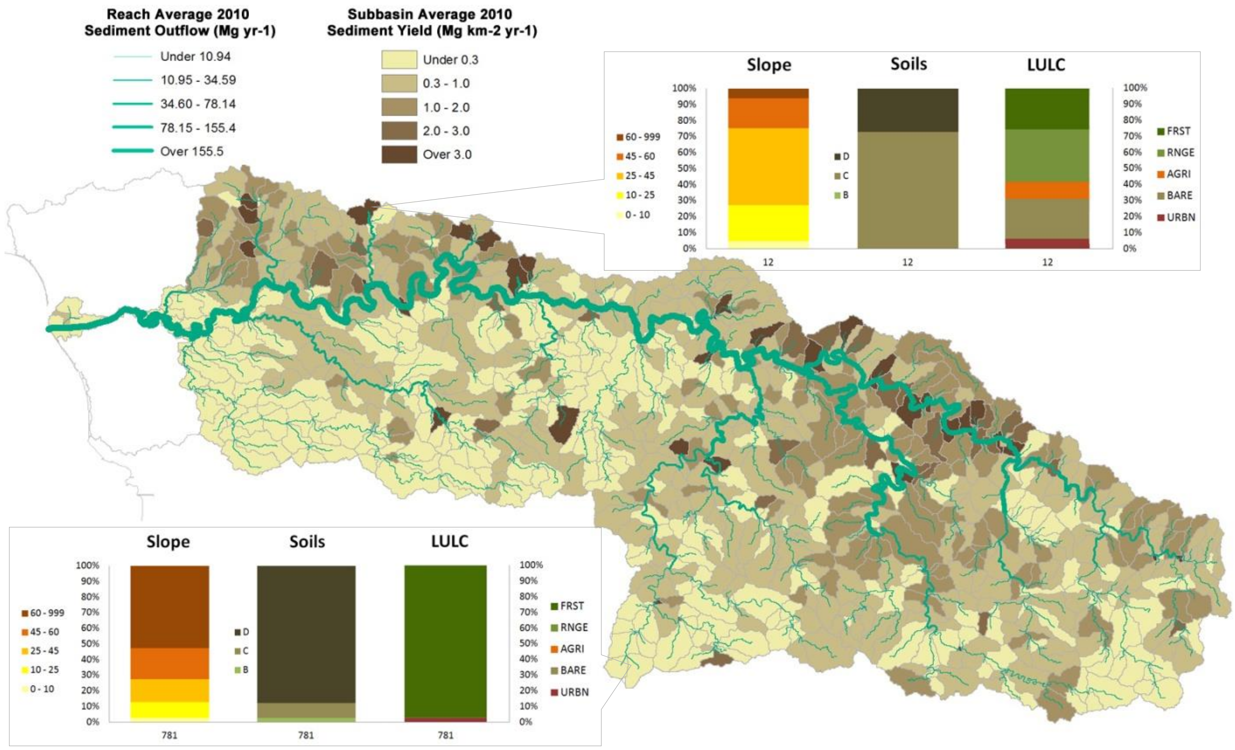


__Figure 20.__ Estimated annual sediment yield per sub-basin and per reach for 2010. Graphic insets describe the distribution of slope, soils and LULC for sub-basins with the higher (12-top right) and lower (781-bottom left) contribution of sediment to the system during time step.

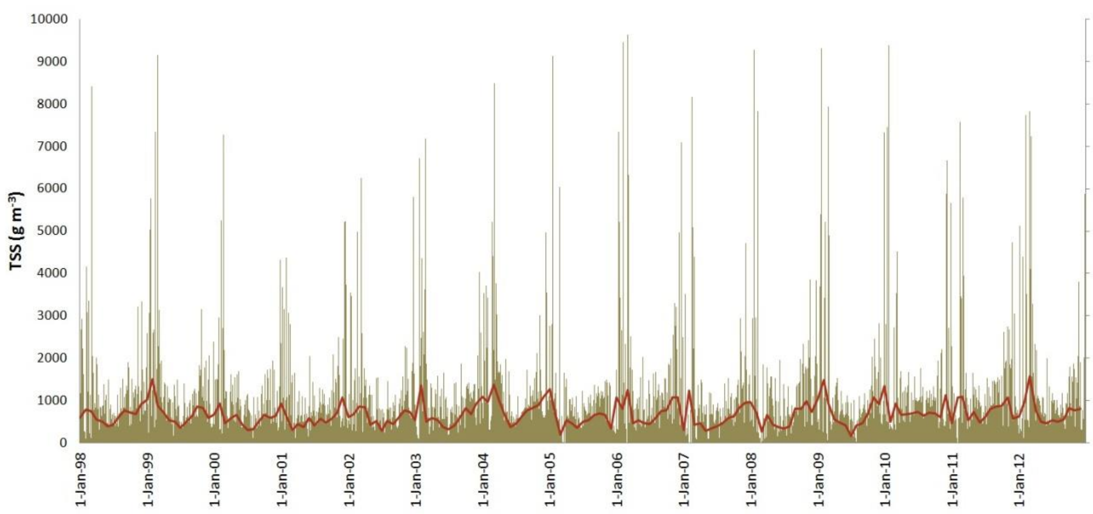


__Figure 21.__ Estimates of daily (brown) and monthly (red) average Total Suspended Solids (g m^{-3}) at the RGA coastal watershed outlet draining into the AM Bay between 1998-2012.

- *RGA Watershed:* Concentration of total suspended sediments values and their characteristic yearly pulses related to drier and wetter seasons are illustrated in Figure 21. Following model calibration and validation, simulated quantities of sediments entering the AM Bay can be further analyzed and correlated with the pulses of the RGA sediment plume and their correspondent temporal and spatial behavior as measured with remote sensing techniques.

SEDIMENT PLUMES- GENERAL TSS TRENDS

Using the Cell Statistics tool, TSS products were geographically summarized under the three different streamflow categories based on 24-hr antecedent discharge ("Low", "Moderate", and "High"). This analysis showed spatial variations in TSS concentration and extent in a cell-by-cell basis (Figure 21). Results showed that the extension of high TSS values in AM Bay was proportional to river flow conditions. During "low flow" conditions, high TSS values (> 3 g m^{-3}) were limited to 2.5 Km from the shoreline. While mean TSS values obtained during "high flow" conditions showed a larger extension of high values that reached up to 9 Km seaward from the RGA main outlet into the bay. On the other hand, TSS values stay regularly high (> 10 g/m^3) within 1 Km surrounding the river mouth even during low river flow conditions.

PLUME MAPPING

A total of 122 river plumes were defined based on TSS values estimated by the MERIS sensor and classified in three categories as previously described (Figure 22). The model assemblage in Model Builder provided an automated method to run in a single step various GIS-based routines and generate two outputs for each of the TSS products. Results from this analysis are stored as polygon feature classes including area extent calculations. The model was built in a way that all outputs are stored in the same location with the name of the original TSS Product plus the specific type of output (Plume or Plume Category). Plume mapping results were evaluated by overlaying generated plume areas and various MERIS RGB composites. The majority of the events showed a good correspondence between visible river plumes and outlined areas (Appendix III). The comparison was made on 13 plumes associated to high river flow (6 plumes) and low river flow events (7 plumes).

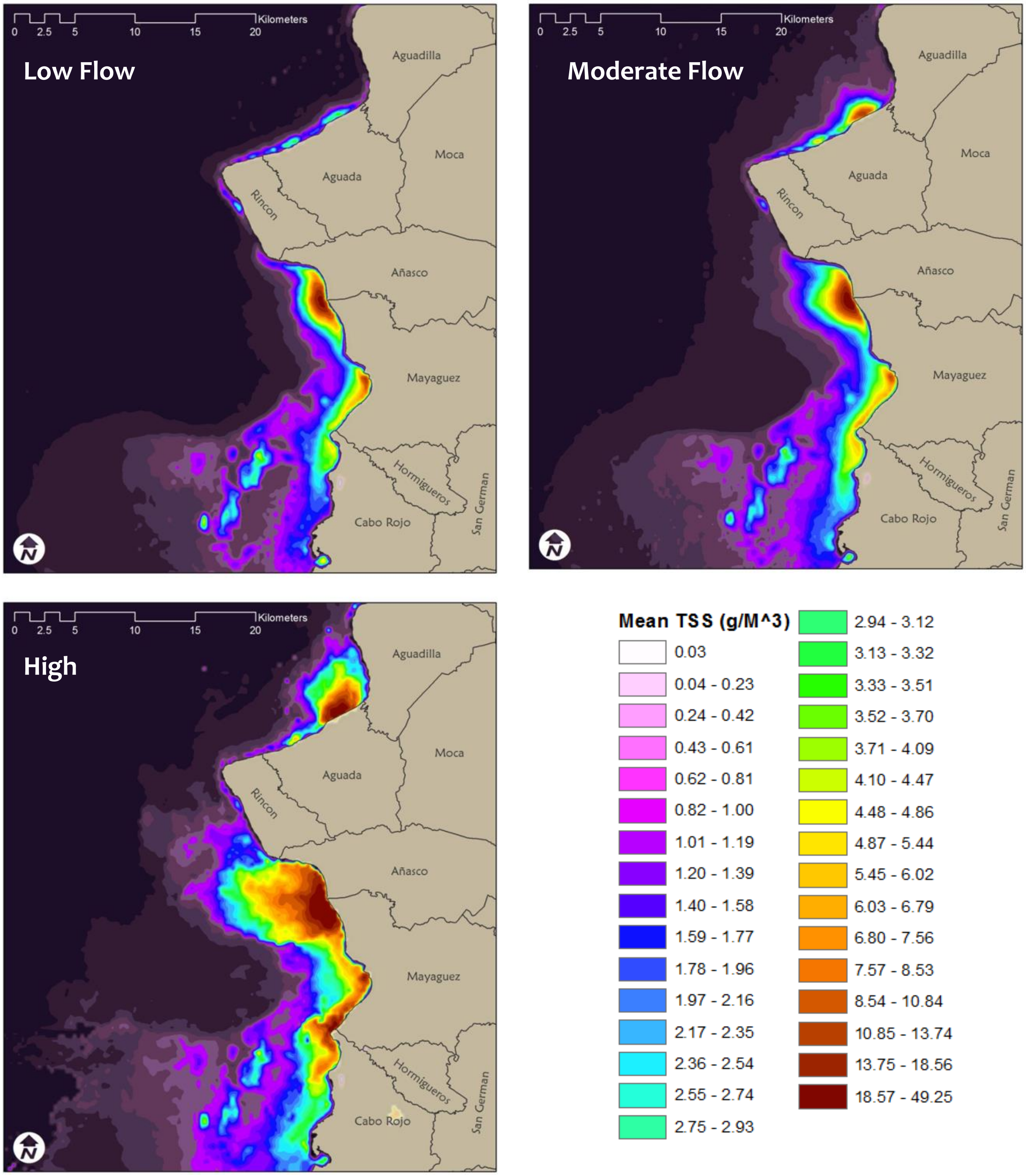


Figure 21. *Mean TSS values obtained after running Cell Statistics to TSS products categorized as described in Table 1 in Appendix III.*

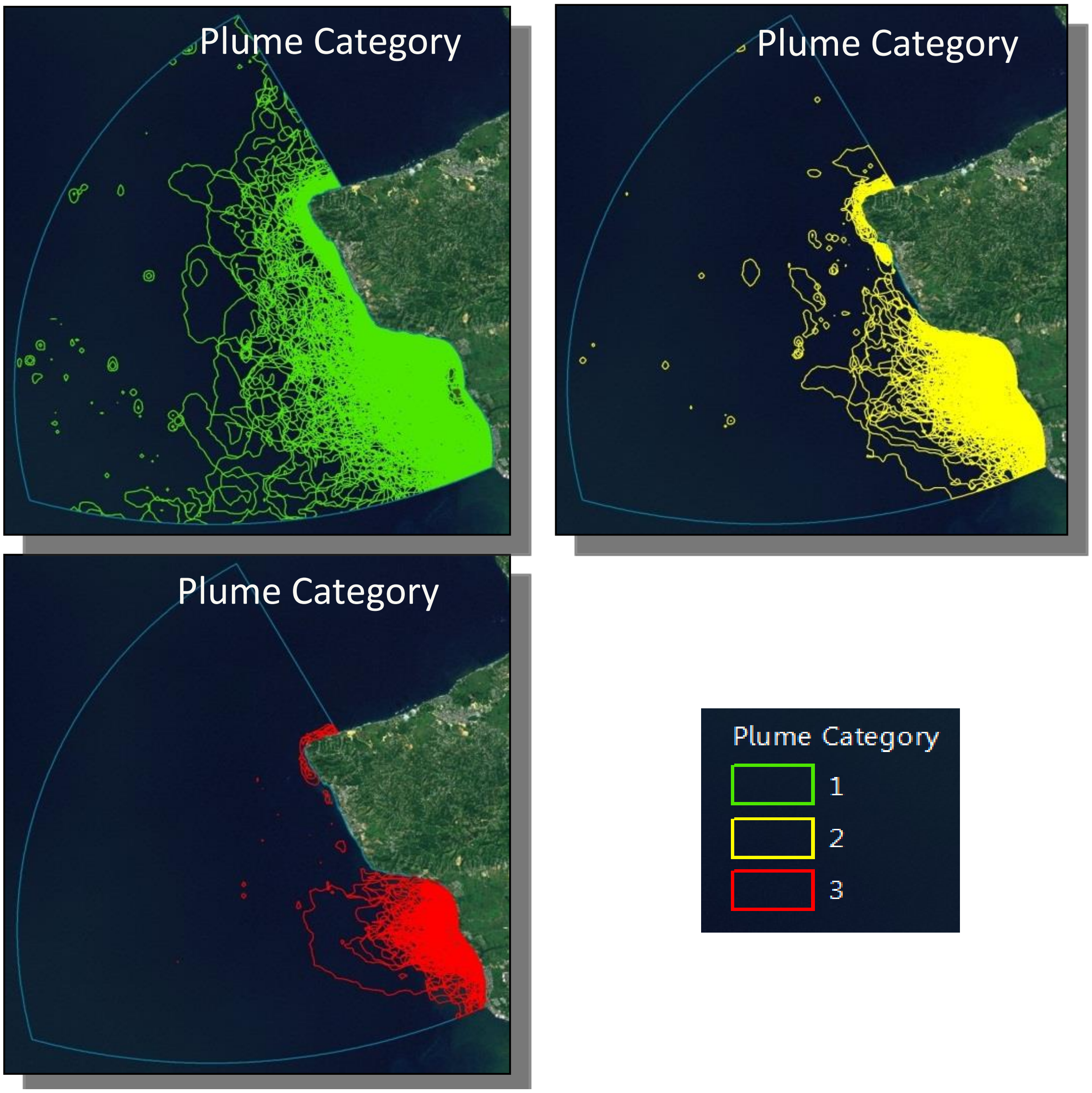


Figure 22. *Spatial extent of all river plumes delimited using a set of pre-defined routines in model builder.*

PLUME DIRECTION ANALYSIS

Mean plume length ranged from 1.09 Km to 6.31 Km considering all seaward directions from the main RGA outlet into AM Bay. Shorter mean lengths were noted towards the north because of the short distance to the shoreline. From 285º Northwest to 165º Southeast the mean length ranged between 4 to 5 Km. This assessment also showed a slightly higher mean length in Transect 5 (300º Northwest), suggesting the preferential extension of the plume in a NW direction. (Figure 23).

Figure 23. *Mean plume length in 14 directions after measuring all 122 outlined plumes*

<u>SPATIAL VISUALIZATION OF CALCULATED CORRELATION COEFFICIENTS</u>

Strong correlation between RGA discharge and plume TSS values were detected in transect points located to the west/west-north between 4 and 13 Km from the shoreline (Figure 24). Moderate correlation dominated the area within 3 Km off the RGA mouth. The maximum instantaneous discharge rate observed in the 24-hr prior to the capture of the MERIS images had the best correlation values in comparison with the other three parameters evaluated (24 Hours Cumulative Discharge, Average Discharge 24 Hours and Median Discharge 24 Hours). This discharge parameter also strongly demonstrates that the highest correlation with MERIS data did not occur in stations closer to the river's mouth. This area maintains very high concentrations of TSS most of the time, regardless of the river flow, which could explain a lower correlation. Moreover, the best correlations are found in areas more sensitive to TSS variations.

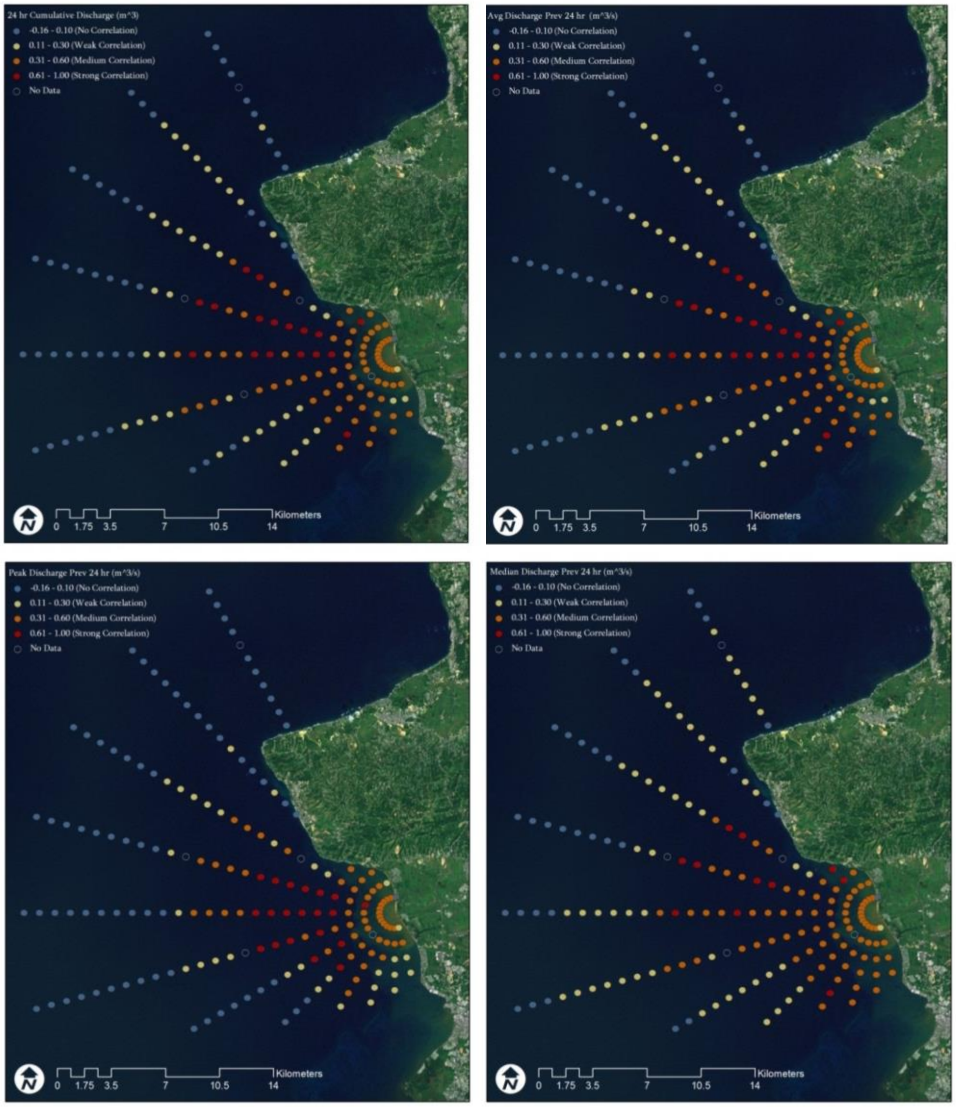


Figure 24. *Spatial distribution of calculated correlation coefficients between TSS values and four river discharge parameters*

<u>EVALUATION OF RIVER PLUME SIZE</u>

Monthly comparisons of average plume size showed larger plumes between August to December (Figure 25). This is in agreement with SWAT model average monthly discharge and sediment yield estimates presented above. When categorized into the three cumulative discharge classes, it became clear that plume size tended to be larger for plumes within the 'high flow' class than those in the "low" or "moderate' flow classes. The same was detected using mean area estimations for each plume category described above (Figure 25). Different river discharge parameters (24-hr cumulative discharge (in m^3), the peak discharge during the previous 24 hours (in m^3 s^{-1}), the average discharge during the previous 24 hours (in m^3 s^{-1}), and the median discharge over the previous 24 hours (in m^3 s^{-1}) were plotted with correspondent plume area extent values in order to detect any potential correlation. The best relationship between plume overall size and RGA discharge as recorded by the USGS streamflow station was with median discharge during the preceding 24 hrs and this was best-fitted by a non-linear exponential relationship (Figure 25).

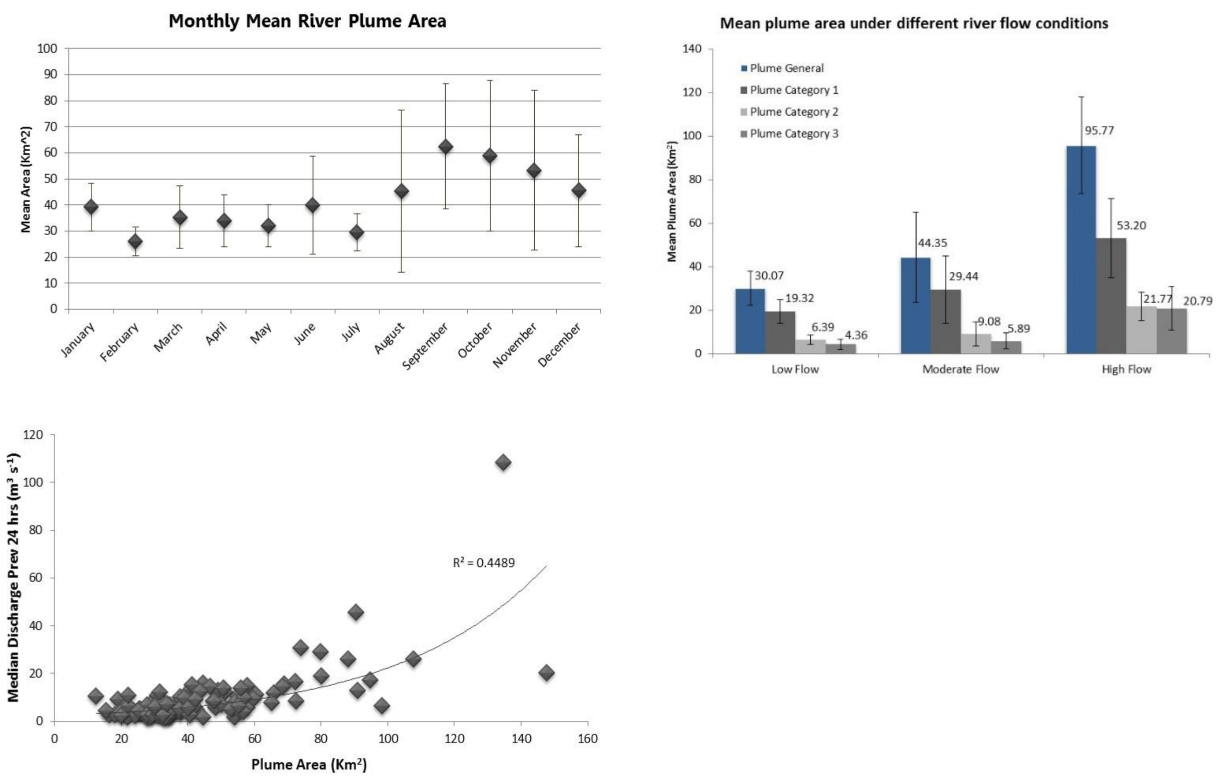


Figure 25. *(a) Mean river plume areas and standard deviations observed on each month; (b) Mean plume area extents and standard deviations observed during three different river flow conditions, and three plume categories; and (c) Exponential trend observed between Median Discharge (24 hrs Prev. the image) and plume area extent*

IV. Objectives accomplished

This project focuses on the following three goals:

1) Apply the SWAT model to estimate runoff and sediment yields from the RGA watershed between 1998 and 2012;
2) Validate and test model results by comparing them to existing runoff and sediment yield data; and
3) Understand how watershed dynamics control the size, spatial distribution, and optical parameters of sediment plumes coming off the RGA outlet into the AM Bay as determined from remotely sensed data.

The following tasks required to fulfill these objectives were accomplished:

- SWAT database development and successful application to the RGA watershed
- Completion of high resolution land cover map based on 2010 imagery
- Frequency distribution analyses of RGA streamflow data
- Initial identification of erosion hotspots and land cover types contributing large quantities of sediment
- MERIS images of sediment plumes were obtained and processed for TSS
- Development of a basic understanding of RGA discharge control on sediment plume size and TSS magnitude

The following tasks are required to fully achieve the abovementioned objectives but are yet to be accomplished:

- Calibration of SWAT model parameters and validation of model outputs are still being completed, therefore all results presented here must be considered as preliminary
- A more formal description of sediment plume behavior based on geo-statistical analyses and that incorporates oceanographic and weather data still needs to be completed
- Completion of two articles to be submitted to refereed journals that position our study in relation to current discussions and management needs

V. Project impacts and products

Specific accomplishments with regards to data gathering and database development were summarized in the methods section.

Among the impacts of this project on watershed and coral reef management strategies we may include the following:

1) Results being used as an initial step in the development of an erosion mitigation strategy for RGA. Attempt to integrate this project's results to NRCS' National Water Quality Initiative in the Río Grande de Añasco watershed were made during an earlier visit to the study area. A meeting took place in November 2012 with Mr. José Castro (NRCS-San Juan) and Zulma García (NRCS-Mayaguez) to discuss the project. NRCS has shown much interest in the results of this project and would like to incorporate the methodology employed in this study in their watershed management strategies. Our erosion 'hotspots' map will be shared with them to help them in selecting areas that merit priority attention. In addition, personnel from the Autoridad de Energía Eléctrica (Ing. Hernán Más and Ing. Jaime López from Hidrogas) have expressed interest in the results of the study as erosion from the areas upstream of the three main reservoirs in the watershed is the main problem they have with the operation of these structures.

2) The study may also have important consequences on how the impact of land-based erosion on coral reef systems is assessed in PR and throughout the Caribbean. A successful application of the SWAT model to the RGA basin may aid in the development of erosion control strategies elsewhere in the region by providing a framework that could be replicated in other climatic and physical settings. The PI is involved in a new study to be conducted in the Río Loco-La Parguera and Río Manatí areas where the model is to be applied and used to guide land management decisions.

3) The study has built on IRF's past and current efforts to study and mitigate the effects of land development and increasing sediment loading rates to coastal waters throughout the Caribbean. IRF has been directly involved in watershed management efforts since the late 1970's, and has been in the forefront of erosion research in the eastern Caribbean since the early 1990's.

4) Through IRF's dissemination efforts we are translating the scientific knowledge gained by this study into practical solutions that can be used by local and regional agencies, NGO's, or community groups to evaluate and mitigate erosion problems. A new project funded by the NASA-HICE program in which this project's PI is involved will quantify on-site erosion rates on cropland areas in the nearby Río Loco watershed. In addition to generating important data, this type of work will permit a one-on-one contact with farmers to help them design better land management strategies.

5) The project has been highlighted at the Department of Geography & the Environment of the University of Texas at Austin website (link) and will likely attract students to work on these issues with the PIs.

6) This project has allowed the continuation of long-term studies of AM Bay by the GERS Lab. Oceanographic and biogeo-optical studies have been conducted in this bay for the past twelve years and land processes are always implicated as important factors for spatial and temporal changes. This study has started to develop quantitative relationships between land and sea connections for a better understanding of this complex ecosystem. This study has also helped to refine remote sensing techniques that have been developed in the AM Bay and can be applied to other coastal areas.

7) Dissemination of study results will target government officials from various agencies (e.g., PR-DNER, NRCS, EPA, Environmental Quality Board, etc.). The PI has already developed projects in partnership with the Coastal Zone Management Program (Mr. Ernesto Díaz) and the Coral Reef Conservation and Management Program) of the PR-Department of Natural and Environmental Resources that will aid the local state agencies in developing methodologies to assess erosion impacts and develop erosion prevention and mitigation strategies. Other partnerships include mitigation and monitoring efforts in the US Virgin Islands as part of NOAA's Coral Reef Protection program. Such partnerships will benefit from the results of this study.

8) Dissemination to the scientific community will continue even after the end date of this study and will take the form in oral and poster presentations in local and international professional conferences and in two publications in professional journals. Different components of this study have become the topic at least three undergraduate honor's theses, which will help to disseminate the studies objectives and results throughout the student body at UPR-Mayaguez. Undergraduate students from the Department of Geography and the Environment have and are still involved in our efforts. Students' responsibilities include participating in local and international conferences to present their results.

9) Fulfilling the project objectives has required training the PI and a research assistant in the use of the SWAT model as well as in model validation and data analyses techniques which will further solidify their background and ability to apply similar techniques elsewhere in Puerto Rico and throughout the US Caribbean.

10) PI's are participating in numerous research-oriented activities in the Caribbean Region. These include similar projects linking watershed dynamics with marine conditions in St. John and St. Croix in the U.S. Virgin Islands and also in Culebra, Fajardo, Cabo Rojo, Río Loco, and La Parguera areas. Collection of field biogeo-optical data in underway in other

coastal areas of Puerto Rico, like in La Parguera and Guánica Bay, to improve the validation and calibration of ocean color sensors, as MODIS and MERIS.

11) This project has developed a methodology that allows better understanding of coupled land-sea dynamics that serves to improve environmental studies of coastal areas. The methods and results developed here help to establish the relationship between the dynamics of the river basin, sediment plumes, and coastal environments, like coral reefs. The project has also produced a set of ArcGIS routines in Model Builder that represent a replicable approach to study the dynamics of river plumes using ocean color images. Although the tool was developed and implemented using TSS from MERIS images, it can be modified to perform similar processing and analyses using other parameters and sensors. Also, the estimation of area extent for each date has added to this study a valuable parameter to assess river plume variations in the study site.

12) Three undergraduate students of the Geology Department worked in specific image processing issues as part of our efforts to improve the monitoring of the Añasco River plume using spaceborne sensors. Ms. Melanie Luna conducted a study titled "Dynamics of the Añasco River Plume as Detected by MODIS and ETM+" that was completed in December 2011 (link). Mr. Luis Palmer conducted a study titled "Improved Monitoring of Suspended Sediments in the Añasco River Plume by Using ETM+" that was completed in May 2012 (link). Both students performed their projects as part of the undergraduate research course Geol 4055 and graduated in May 2012. More recently Mr. Josué Aceituno Díaz conducted the research project titled "Characterizing the Añasco River Plume using MERIS" that was completed in May 2013 (link). He also made a second project titled "Mapping the Frequency and Distribution of the Rio Grande de Añasco Plume using MERIS that was completed in December 2013 (link). Mr. Aceituno performed their projects as part of the undergraduate research courses Geol 4049 and Geol 4055 and graduated in May 2014.

13) PI Ramos Scharrón has served as manager or principal investigator of four watershed restoration projects in St. John-St. Croix-USVI, Vieques, and Culebra (NOAA-ARRA, PR-DNER, NOAA-Coral Reef Restoration, EPA), a watershed assessment, sediment plume, and coral reef condition project in Cabo Rojo (PR-DNER), and two research projects in Fajardo and Parguera (UPR-CCRI). In addition, the PI is currently part of a new NASA-HICE funded project in partnership with UPR-Río Piedras in the Río Loco-Parguera and Río Manatí areas and is leading the efforts of LLILAS-Benson's Interdisciplinary Environmental Studies Initiative of the University of Texas at Austin. The first project scheduled to be developed as part of this initiative is intended to take place in Puerto Rico and will have a very similar, yet more encompassing, set of objectives as this project.

14) A site-specific algorithm has been developed and tested to estimate Total Suspended Sediments (TSS) in Mayaguez Bay. This algorithm is being incorporated in NOAA-

NESDIS system as a "testing product" of TSS for Puerto Rico in collaboration with Joaquin Trinanes, Acting NOAA Coast Watch Operations Manager for the Caribbean Regional Node.

15) Co-PI Gilbes has been conducting in collaboration with researchers from University of South Florida the NSF-funded project "Coastal Areas Climate Change Education (CACCE) Partnership". Our current activities are focused on bringing together an effective set of educational, professional and public partners to meet the varied needs of these audiences across our region, and tailoring an educational plan that starts with the regionally and topically relevant impacts of climate change, and strategies for effective adaptation and mitigation.

16) Although few presentations that directly deal with the research described in this report may be listed, both PI's have continued to make presentations on the general subject of watershed analyses and on the use of remote sensing techniques to describe the effects of land-based sources of pollution into the marine environment of the Caribbean. Below is a list of presentations made by the PIs while this project was active:

- "*Historical and contemporary human use of the land and its environmental legacy in the Northeastern Caribbean*", LLILAS New Faculty Talk Series, 28-Mar-2014.

- "*Application of the Soil and Water Assessment Tool Model (SWAT) to estimate discharge and sediment yields from the Río Grande de Añasco Watershed, Puerto Rico*", 5th UPR Sea Grant College Program Research Symposium, 20-Feb-2014, Mayaguez, PR.

- "*Road sediment production and delivery: Processes, rates, and possible improvements*", Poster presented by L. MacDonald, EGU General Assembly 2013, 11-Apr-2013, Vienna, Austria.

- "*Interdisciplinary approaches to assess the hydro-geomorphological effects of land use change on marine ecosystems of Puerto Rico and the U.S. Virgin Islands*", Geological Society of America Meeting of the Southern Section, 20-21 March 2013.

- "*The impact of watershed development and restoration on marine sedimentation on coral reefs in St. John, U.S. Virgin Islands*", Presented by S. Gray, Geological Society of America Meeting of the Southern Section, 20-21 March 2013.

- "*Improving climate change education in the Caribbean region*", Geological Society of America Meeting of the Southern Section, 20-21 March 2013.

- *"Experience of a Collaborative Partnership to Improve the Education about Climate Change in Puerto Rico"*, XII Puerto Rican Congress on Research in Education, San Juan, Puerto Rico, March 8, 2013.

- "*An interdisciplinary erosion mitigation approach for coral reef protection- A case study from the Eastern Caribbean*", Presented by J. Amador, 8th International Multi-Purpose Reef & Surfing Science Symposium, 19-21 February 2013. Rincón, PR.

- "*The effects of unpaved roads on suspended sediment concentration of third- to fifth-order streams – A case study from southern Brazil*", AGU Fall Meeting, 3 December 2012, EP13D-0080 (poster).

- "*Ridge to reef assessment of metal concentration and mineralogy in rocks and sediments on St. John, U.S. Virgin Islands*", AGU Fall Meeting, 3 December 2012, EP13D-0884 (poster).

- "*Land Use and Hydro-Geomorphology*", A one-day Geography graduate student course given at UNICENTRO, Guarapuava, Paraná, Brasil, 5 July 2012.

- "*An interdisciplinary erosion mitigation approach for coral reef protection- A case study from Culebra, Puerto Rico*", Quantifying Sustainability in Puerto Rico-EPA Sponsored Conference, San Juan, Puerto Rico, 5-7 June 2012.

17) Although no journal articles that directly deal with the research completed as part of this project may be listed, both PI's have continued to publish articles on the general subject of watershed analyses and on the use of remote sensing techniques to describe the effects of land-based sources of pollution into the marine environment of the Caribbean. Below is a list of already published and upcoming publications completed while this project was active:

- Ramos-Scharrón CE, Reale-Munroe K, Atkinson S, 2014. Quantification and modeling of foot trail surface erosion in a dry sub-tropical setting. *Earth Surface Processes and Landforms.* DOI: 10.1002/esp.3558.

- Bégin C, Brooks G, Larson R, Dragcevic S, Ramos-Scharrón CE, Côte IM. 2014. Increase in sediment loads over coral reefs in Saint Lucia in relation to changes in land use in contributing watersheds. *Ocean and Coastal Management,* 95: 35-45.

- Thomaz E, Vestena LR, Ramos-Scharrón CE, 2013. The effects of unpaved roads on suspended sediment concentration of third- to fifth-order streams – A case study from southern Brazil. *Water and Environment Journal*. DOI: 10.1111/wej.12070.

- Ramos-Scharrón CE, Hernández-Delgado E, Torres-Pulliza, D. in revision. Watershed-scale land cover changes in northeastern Puerto Rico, 1936-2004. Submitted to *Ambio* (Revision submitted May-2014).

- Reale-Munroe K, Castillo B II, Ramos-Scharrón CE. 2011. Measurement of particulate organic material and erosion rates in small subtropical watersheds on the East End of St. Croix, U.S. Virgin Islands. Report to the Water Resources Research Institute, University of the Virgin Islands, Project No. 2010VI-170B, 34 p.

- Island Resources Foundation. 2012. Virgin Gorda-Environmental Profile.

- Ramos-Scharrón CE, Reale-Munroe K, Swanson B, Atkinson S, Devine B. 2012. USVI Coastal Habitat Restoration through Watershed Stabilization Project, NOAA-ARRA, 2009-2012, Terrestrial Monitoring Component. Unpublished Report to NOAA-Coral Reef Protection Program. 242 p.

- Ramos-Scharrón CE, Amador J, Colón-López J. 2012. Guidelines for the development of an erosion control program to reduce sediment loading rates from the unpaved road network in the island of Culebra-Puerto Rico. Coastal Zone Management Program, PR-Department of Natural and Environmental Resources.

- Hernández-Delgado E, Ramos-Scharrón CE, Guerrero-Pérez C, Lucking MA, Laureano R, Méndez-Lázaro PA, Meléndez-Díaz JO. 2012. Development in tropical coastal habitats in a changing climate: lessons learned from Puerto Rico (Chapter 18). In: M Kasimoglu (Ed.), "Visions for Global Tourism Industry-Creating and Sustaining Competitive Strategies", InTech Publications, Croatia, pp. 357-398.

- Ramos-Scharrón CE, Amador-Gutierrez J, Hernández-Delgado E, 2012. An interdisciplinary erosion mitigation approach for coral reef protection- A case study from the Eastern Caribbean (Chapter 6). In: Marine Ecosystems- Intech Publications, pp. 127-160.

- Ramos-Scharrón CE, 2012. Effectiveness of an erosion control method in reducing sediment production rates from an unpaved road. *Journal of Soil and Water Conservation* 67(2): 87-100.

VI. Recommendations

1. The spatial and temporal analyses of the Añasco River plume were possible using MERIS images. However, several limitations were detected based on sensor capabilities and atmospheric conditions. The fact that MERIS data is no longer available it makes necessary to find another sensor suitable for the estimation of suspended sediments in places like AM Bay. A high spatial and temporal resolution is required in order to

obtain the best estimates of TSS. Sensors like VIIRS (Visible Infrared Imager Radiometer Suite) that is currently in orbit and OLCI (Ocean Land Color Instrument) to be launched in 2015 should be tested for TSS estimation and plume analyses using the methodology developed in this project.

2. Although the expert visual interpretation approach for developing the land cover map proved to deliver the highest level of mapping detail and clarity, feature boundaries delineation can be subjective. Moreover, with over 370 hours dedicated only to the mapping and editing process, it was considered highly time consuming and labor intensive. Overall, high resolution land cover visual interpretation of a relatively large RGA watershed was considered time and resource inefficient. Other hybrid remote sensing mapping techniques, that still provide for detailed HRUs scale analyses, should be considered for future efforts.

3. Data analysis and quantitative mapping of SWAT simulation outputs helped identify areas where unique combinations of soils, LULC and slope contributed the higher amounts of sediment to the system. In cases, those HRUs erosion hotspots were depicted in areas close to the reach or even at the river headwaters, situation that not only promote river and coastal water quality degradation but also impacts the ecological balance of the river source itself. Analysis also emphasizes that reforestation of the known erosion hotspots is a feasible and effective practice to minimize sediment loss and consequential discharge into AM Bay. This efforts attempt to guide managers prioritizing areas for land management practices that will potentially help reduce further terrestrial impacts on nearshore coral reefs.

4. According to SWAT current land cover patterns in RGA have no effect in the amount of discharge being delivered to AM Bay relative to baseline conditions. In contrast, current sediment yields were estimated about an order of magnitude higher than those under a fully forested watershed. This highlights the impact that current human activities are having in erosion and sediment yields and the need for the implementation of management strategies meant to mitigate these effects.

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APPENDICES

APPENDIX I

RGA LAND COVER MAP

INTRODUCTION

This Appendix describes the process of generating a 2010 land cover (LC) map for the Río Grande de Añasco (RGA) Watershed. Land cover categories for the 517 km^2 RGA watershed (Figure 1) were digitized, at a mapping scale of 1:5000, by means of visual interpretation of a Leica ADS40 orthographic image with a 0.3 meter spatial resolution. The source orthoimage was collected between October 2009 through January 2010 by request of the United States Army Corps of Engineers and was kindly made available for this project. The resulting 2010 LC data layer was partially ground-truthed based on field data and pre-existing digital maps.

MATERIALS AND METHODS

Fieldwork

Field work was conducted on the 18-19 January 2012. A total of 174 kilometers were traveled within the watershed and 144 GPS data points were collected (Figure 1). Descriptive information of existing land cover was registered to the left and right of the road for a total of 288 observations. Field visits were especially useful to verify land cover categories previously identified as dubious and, for general recognizance and familiarization with current watershed management practices taking place (Figure 2). Visual recognition of land uses was complemented by conversations with local farmers to obtain a better understanding of agricultural practices and uses.

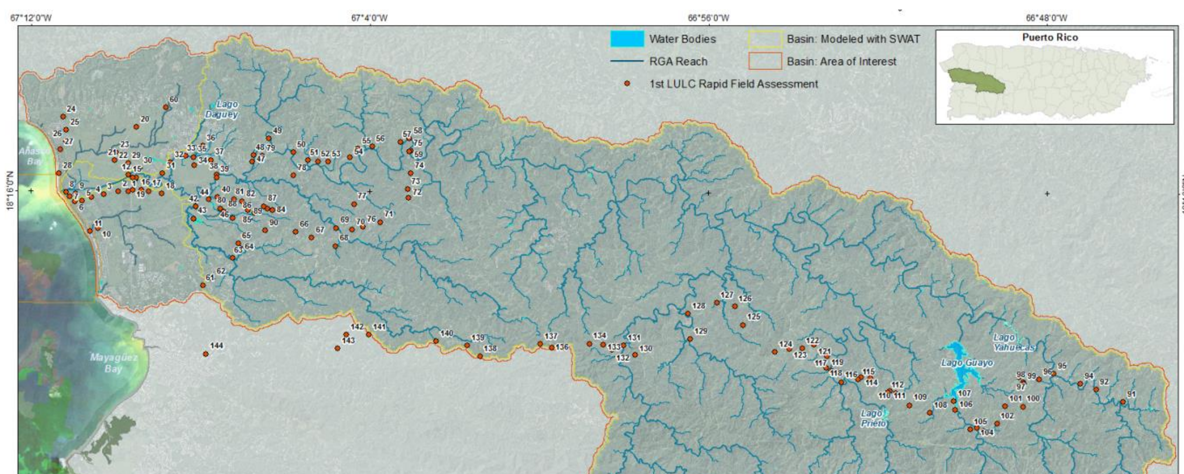


Figure 1. RGA watershed showing points where land cover classes were verified in the field.

Figure 2. *Samples of the different land cover classes currently occupying the Río Grande de Añasco watershed.*

Ancillary Digital Data

The base imagery to conduct the land cover mapping was collected by the multispectral imaging sensor Leica ADS40 between October 2009 and January 2010 (*see*: 2009-2010 Puerto Rico USACE ADS40) (Figure 3). The accuracy and level of detail this data set at a 0.3 m resolution allowed for the development of a land cover thematic layer at a mapping scale of 1:5000. An orthographic ADS40 image collected from November 2006 through March 2007, also developed for the United State Corps of Engineers at a ground sample distance of 0.3 meters (*see*: 2006-2007 Puerto Rico USACE ADS40), also served as mapping support for areas where the base imagery presented cloud cover and as visual aid for land cover interpretation of unclear landscape patterns.

Existing land use digital maps were also useful for general knowledge-based interpretation. Digital landuse data layers included: The Puerto Rico Gap Analysis Project land cover map generated from image classification of 1999-2003 Landsat ETM+ imagery; the PRWRERI/UPRM

Land Use Map using a 2004 Landsat TM imagery and aerial photography of 1997 and; the USGS NLCD 2001 based on unsupervised classification of 2001 Landsat ETM+ imagery (Figure 3). Although generated from different data sources, classification schemes and, spatial and temporal scales, these data layers incorporate a level of accuracy that is valuable for general guidance and, eventually, for broad land cover change analyses.

Image Classification

Manual visual interpretation techniques were selected over automated image classification methods for land cover mapping mainly to provide continuity with the methodology adopted to create land cover maps in neighboring watersheds for other similar projects being conducted by the Principal Investigator and research associates. Also, given the lack of a near infrared image band which is considered useful to spectrally discriminate between vegetation types, it was considered appropriate to follow visual interpretation techniques as a mean to capture and visually validate small agricultural areas, or even shade grown crops such as coffee at a 1:5000 mapping scale.

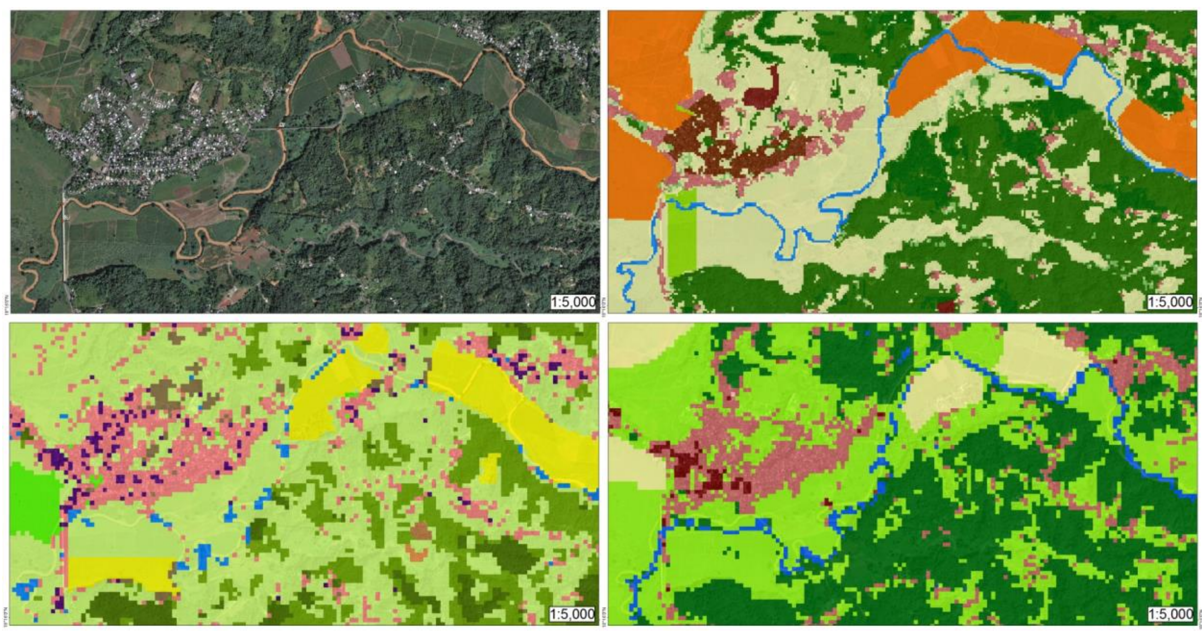


Figure 3. *Sample of ancillary data used to guide visual interpretation: (top left) 2010 ADS40 base image; (top right) PRGAP, (bottom left) PRWRERI; (bottom right) NLCD.*

The watershed was delineated based on a high resolution Digital Elevation Model using SWAT automated basing delineation tools. A buffer zone with 100 meters distance was generated around the external limits of RGA watershed for continuity and in order to include any neighboring feature relevant to the RGA hydrologic system. Therefore, although the RGA planimetric watershed area as initially delineated by SWAT is around 517 km^2, the mapping area is actually about 533 km^2. Visual cues such as class-specific patterns, textures, shapes or ecotones were key to generate the RGA thematic data layer.

Additional visual interpretation contextual aids exploited for knowledge-based thematic mapping included field visits, existing historical land use maps, aerial photography series not included in the analysis and archived Landsat satellite imagery. Furthermore, a single photo analyst carried out the entire mapping process in an attempt to minimize consistency errors. The land cover classification scheme was generally based on Anderson et al. (1976) and yielded twenty nine thematic classes at Level III of the hierarchical classification scheme and seventeen at Level II (Table 1). The classification scheme adopted considered land cover categories that are proper to accommodate the SWAT model requirements.

Final Notes

Although the expert visual interpretation approach proved to deliver the highest level of mapping detail and clarity, feature boundaries delineation can be subjective. Moreover, with over 370 hours dedicated only to the mapping and editing process, it was considered highly time consuming and labor intensive. Overall, high resolution land cover visual interpretation of a relatively large RGA watershed was considered time and resource inefficient. Other hybrid remote sensing mapping techniques should be considered for future efforts.

During the mapping exercise several ongoing deforestation areas were identified. Based on the imagery used, it was also noticed a prevailing brownish main river coloration all the way upland, with few areas of clear water directly associated with dense and extensive forest lands. The type or resolution delivered by the ADS40 imagery allowed in some case to infer deficient erosion control management practices as well.

APPENDIX II

WEATHER AND DISCHARGE DATA

Figure 1. Daily Rainfall and Min/Max Temperature for one of the twelve rain gauges found within or near the periphery of RGA (i.e. Adjuntas/660061)

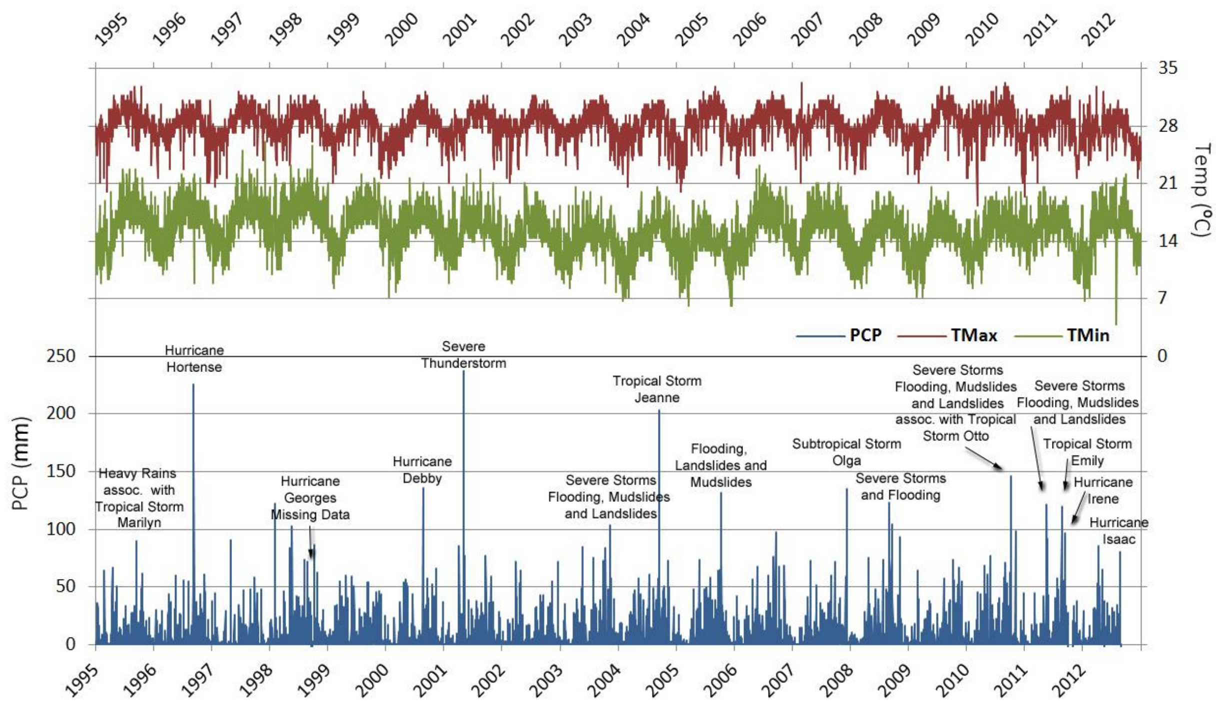
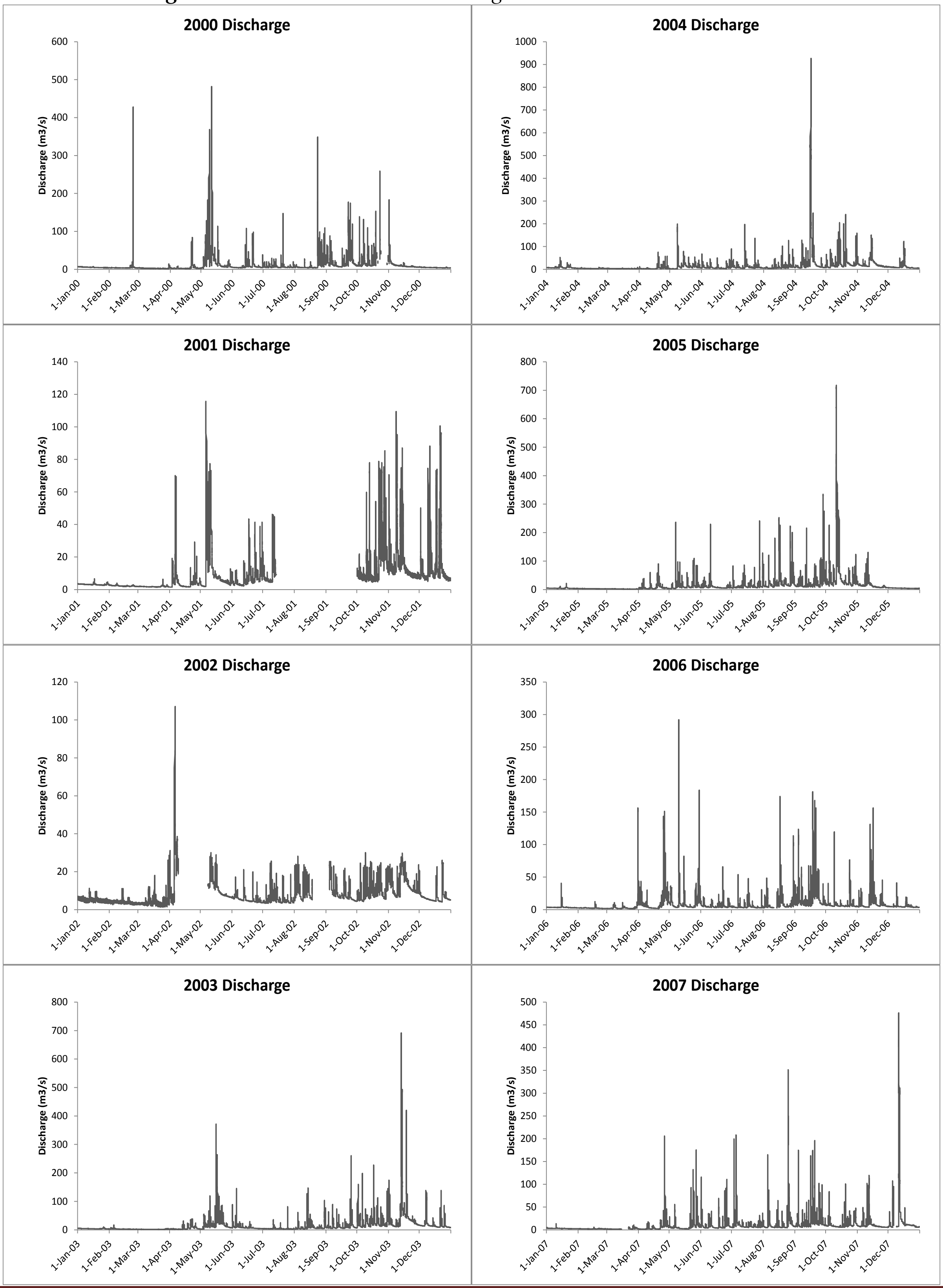
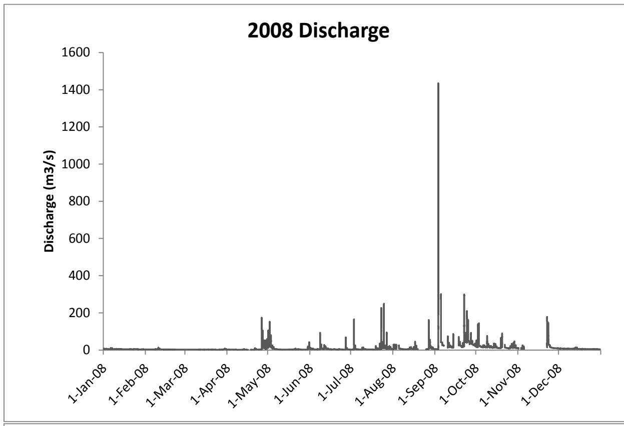
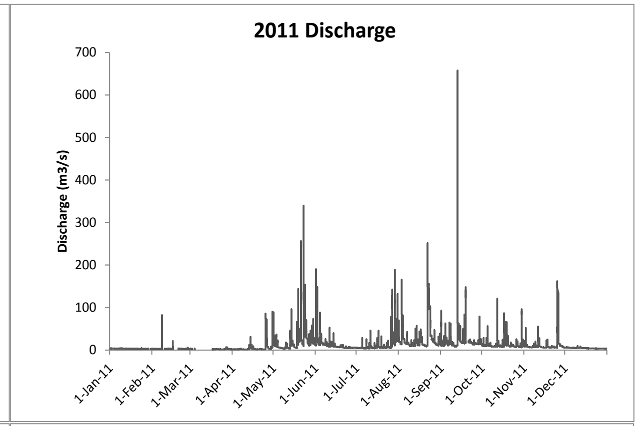
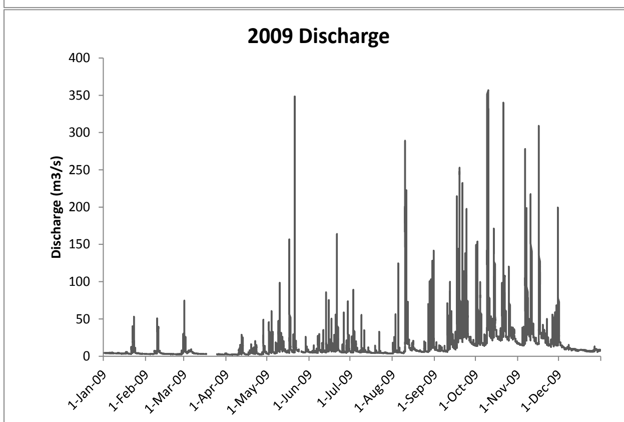


Figure 2. *15-min Resolution Discharge Data USGS 50144000 station*




2008 Discharge
Discharge (m3/s)
0
200
400
600
800
1000
1200
1400
1600
1-Jan-08
1-Feb-08
1-Mar-08
1-Apr-08
1-May-08
1-Jun-08
1-Jul-08
1-Aug-08
1-Sep-08
1-Oct-08
1-Nov-08
1-Dec-08


2011 Discharge
Discharge (m3/s)
0
100
200
300
400
500
600
700
1-Jan-11
1-Feb-11
1-Mar-11
1-Apr-11
1-May-11
1-Jun-11
1-Jul-11
1-Aug-11
1-Sep-11
1-Oct-11
1-Nov-11
1-Dec-11


2009 Discharge
Discharge (m3/s)
0
50
100
150
200
250
300
350
400
1-Jan-09
1-Feb-09
1-Mar-09
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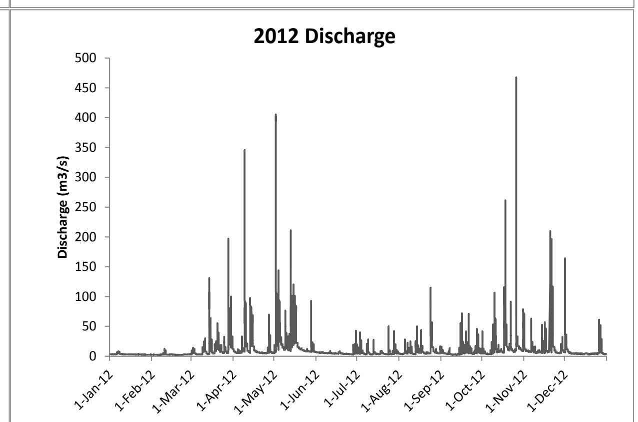
1-Nov-09
1-Dec-09


2012 Discharge
Discharge (m3/s)
0
50
100
150
200
250
300
350
400
450
500
1-Jan-12
1-Feb-12
1-Mar-12
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1-Nov-12
1-Dec-12

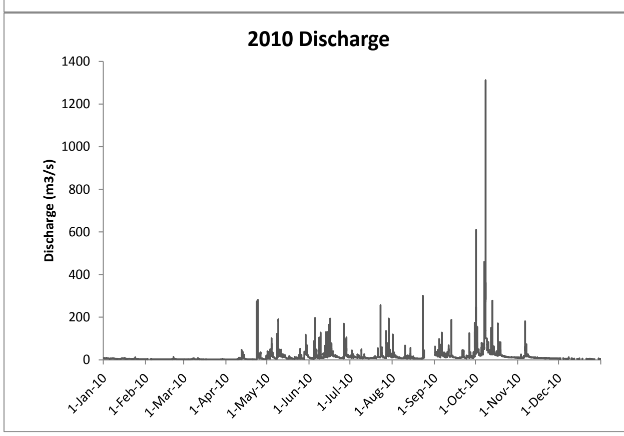
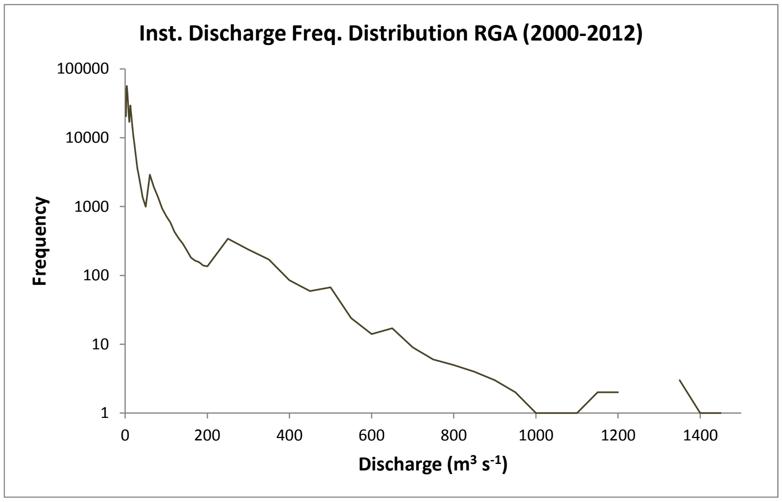

2010 Discharge
Discharge (m3/s)
0
200
400
600
800
1000
1200
1400
1-Jan-10
1-Feb-10
1-Mar-10
1-Apr-10
1-May-10
1-Jun-10
1-Jul-10
1-Aug-10
1-Sep-10
1-Oct-10
1-Nov-10
1-Dec-10

Figure 3. *Frequency distribution curves for 15-min streamflow data for the RGA USGS 50144000 station (2000-2012).*



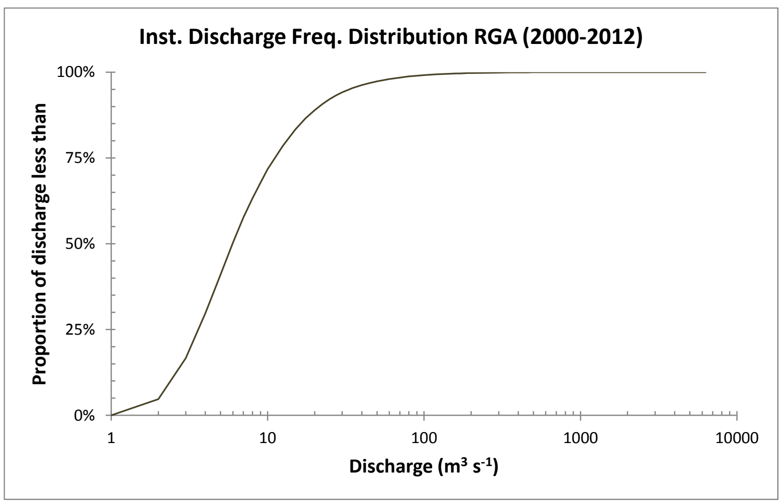


Figure 4. *Cumulative discharge data for time periods extending from 4-hrs to 72-hrs for year 2000*

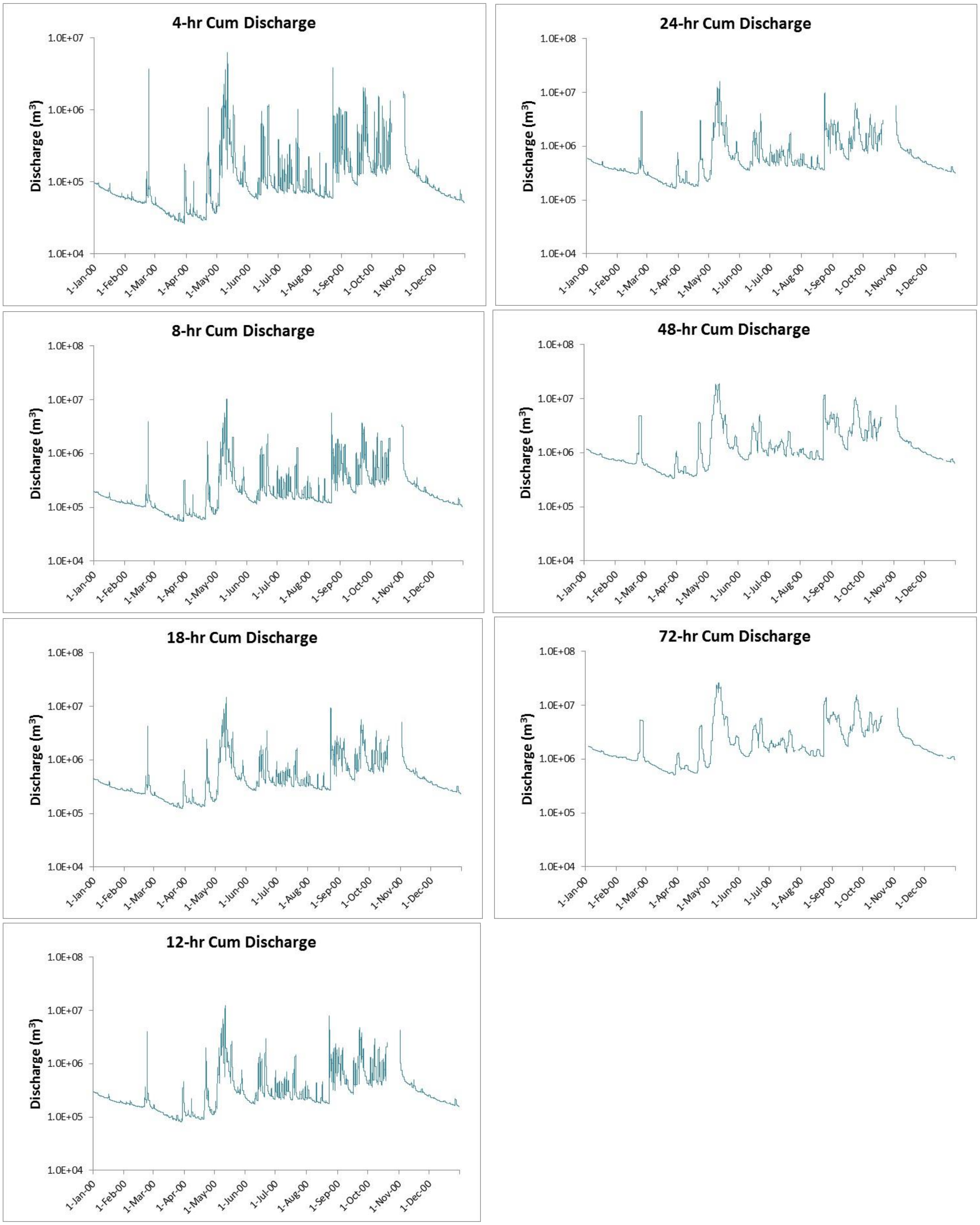
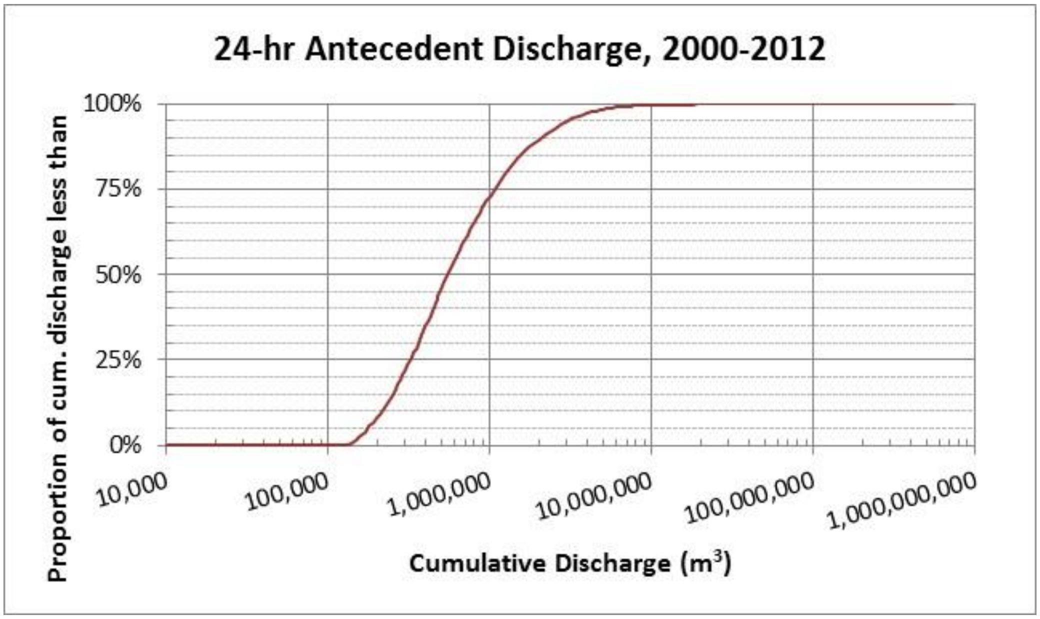


__Figure 5.__ Cumulative 24-hr antecedent discharge frequency distribution for the 2000-2012 period at RGA near San Sebastián stream gauging station.



In this figure, the *"Very Low"* values represent cumulative discharge that was exceeded by 90% of the time between 2000 and 2010. "Low" cumulative discharge values represent conditions for which 10% of the time discharge was lower but for which 75% cumulative discharge was higher. The combination of these two categories represents the lower quantile of the total distribution of cumulative flows and was used to categorize sediment plumes into a *"Low Flow"* category. Thirty of the MERIS-derived sediment plumes belonged in this category.

"Medium Flow" conditions are those for which cumulative discharge was lower 25% of the time but for which flow rates also exceeded these values 25% of the time (*"Medium low"* and *"Medium High"*). This category includes the median cumulative discharge value (50%; between 1,750,000 and 2,000,000 m^3) and includes all flows within a quartile of the median flow (from 25% to 75% of the flow frequency distribution). Eighty-six of the sediment plumes studied here were considered to fall within this category.

"High Flow" conditions are those for which the cumulative discharge measured between 2000 and 2010 at RGA was lower 75% of the time. This category includes all of the highest flow (or wettest) periods as it contains all flows that fall within the upper 25% quartile of the frequency distribution. Six sediment plumes studied here were found to fall within this category, but no sediment plume represents flow conditions that fell within the *"Very High"* category.

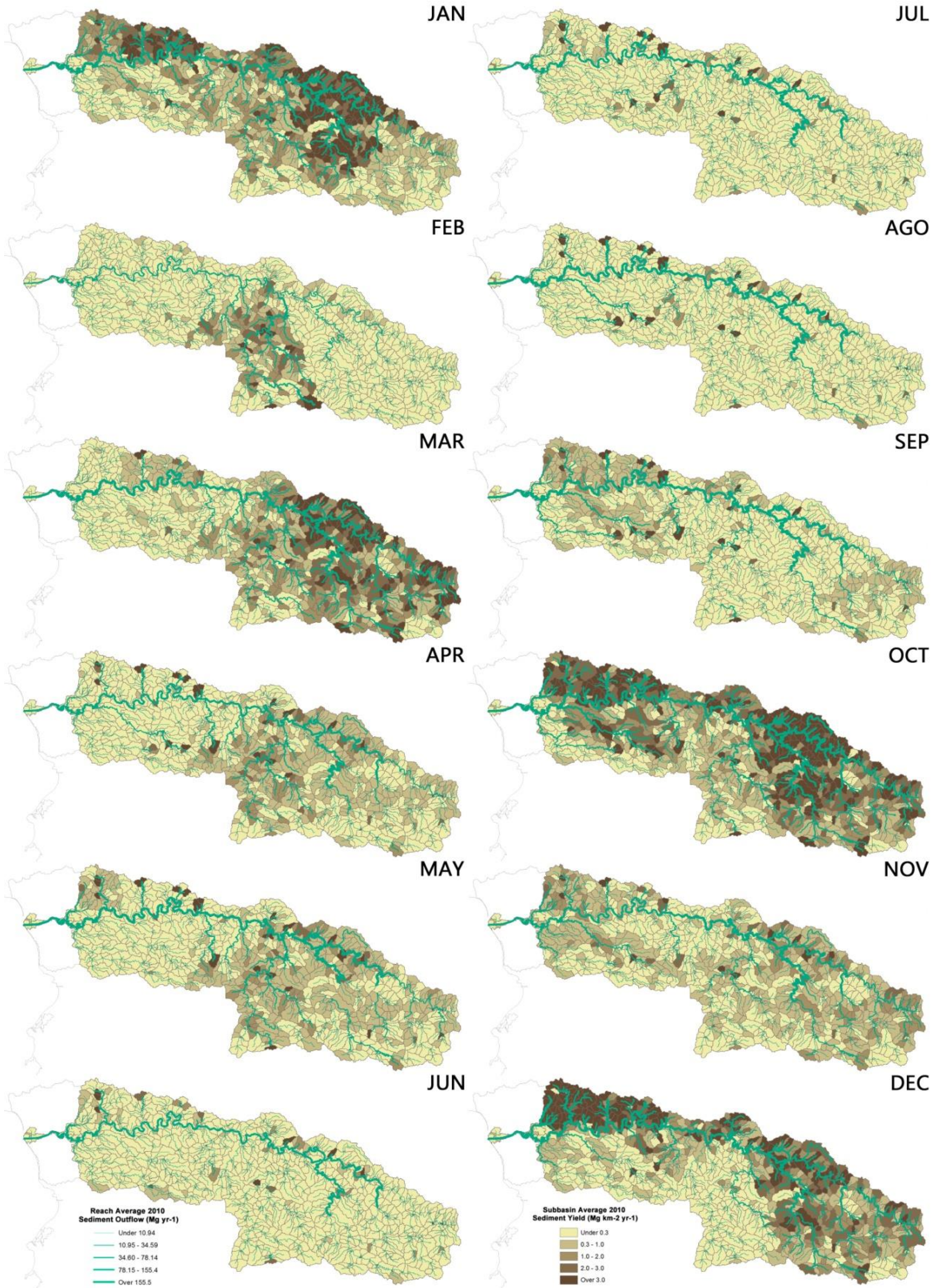


Figure 6. *Estimated monthly sediment yield per subbasin and per reach for 2010.*

APPENDIX III

ANCILLARY SEDIMENT PLUME DATA

Table 1. *Date, cumulative discharge and river flow category of all TSS products used for analysis*

Date	Cum Discharge[1] (m^3)	Date	Cum Discharge[1] (m^3)	Date	Cum Discharge[1] (m^3)	Date	Cum Discharge[1] (m^3)
Low Flow							
2/24/2005	234,465	7/15/2006	295,447	2/26/2008	217,811	2/23/2009	229,517
3/2/2005	222,146	12/27/2006	314,014	3/10/2008	175,498	2/26/2009	249,360
3/5/2005	214,444	1/18/2007	268,106	3/13/2008	173,050	3/27/2009	228,854
3/8/2005	216,586	1/31/2007	207,838	3/26/2008	156,752	4/18/2009	298,380
3/24/2005	153,513	3/7/2007	148,820	3/29/2008	162,389	3/15/2010	216,714
3/12/2006	159,430	5/16/2007	212,378	5/19/2008	251,528	1/27/2011	225,385
3/22/2006	160,603	2/20/2008	230,002	1/19/2009	312,918		
3/25/2006	142,061	2/23/2008	218,703	2/4/2009	251,885		
Moderate Flow							
4/22/2005	1,218,821	11/6/2006	511,880	11/7/2007	1,410,693	1/25/2009	352,374
4/25/2005	578,244	11/9/2006	362,320	11/10/2007	968,313	3/1/2009	1,003,102
5/27/2005	732,063	11/12/2006	336,102	11/23/2007	605,610	5/1/2009	326,155
6/15/2005	698,753	11/22/2006	484,004	12/18/2007	1,151,310	5/4/2009	505,096
8/5/2005	805,185	11/25/2006	651,748	12/31/2007	551,897	5/30/2009	855,582
9/12/2005	1,480,576	12/8/2006	416,977	1/6/2008	548,633	6/8/2009	1,213,847
9/19/2005	1,586,599	12/11/2006	450,286	1/22/2008	343,345	8/14/2009	934,749
11/8/2005	1,020,802	1/2/2007	329,674	1/25/2008	431,081	11/27/2009	1,789,821
11/15/2005	1,285,924	3/29/2007	403,995	4/30/2008	1,561,579	12/6/2009	860,045
11/18/2005	854,052	4/11/2007	517,236	7/25/2008	975,735	12/22/2009	568,832
12/13/2005	418,048	4/30/2007	652,845	7/28/2008	1,654,620	12/26/2009	568,756
12/23/2005	355,944	6/23/2007	647,795	8/16/2008	513,640	1/1/2010	721,810
12/29/2005	325,237	6/29/2007	705,053	8/29/2008	1,333,363	7/18/2011	555,901
1/1/2006	344,187	7/25/2007	535,396	10/6/2008	1,350,349	9/16/2011	1,827,619
3/9/2006	436,284	7/28/2007	645,143	10/9/2008	1,295,845	10/5/2011	1,171,662
5/15/2006	521,674	8/13/2007	689,087	10/28/2008	1,402,659	10/16/2011	621,449
6/19/2006	633,818	8/29/2007	1,252,028	11/26/2008	1,081,070	10/19/2011	1,878,016
7/8/2006	909,168	9/1/2007	620,785	11/29/2008	843,085	10/27/2011	1,278,935
8/19/2006	2,072,337	9/11/2007	1,241,392	12/2/2008	744,126	11/1/2011	802,736
9/16/2006	533,559	10/3/2007	783,225	12/12/2008	579,289	11/12/2011	2,072,567
10/24/2006	431,311	10/9/2007	692,275	12/31/2008	386,397		
11/3/2006	810,566	10/19/2007	621,984	1/22/2009	556,947		
High Flow							
9/28/2005	3,268,280	10/17/2005	2,521,527	8/11/2009	7,476,920	9/18/2009	4,620,720
10/14/2005	11,260,600	10/20/2005	2,514,283				

[1] Data collected by USGS gauging station (USGS 50144000) 24 hrs previous to MERIS image time

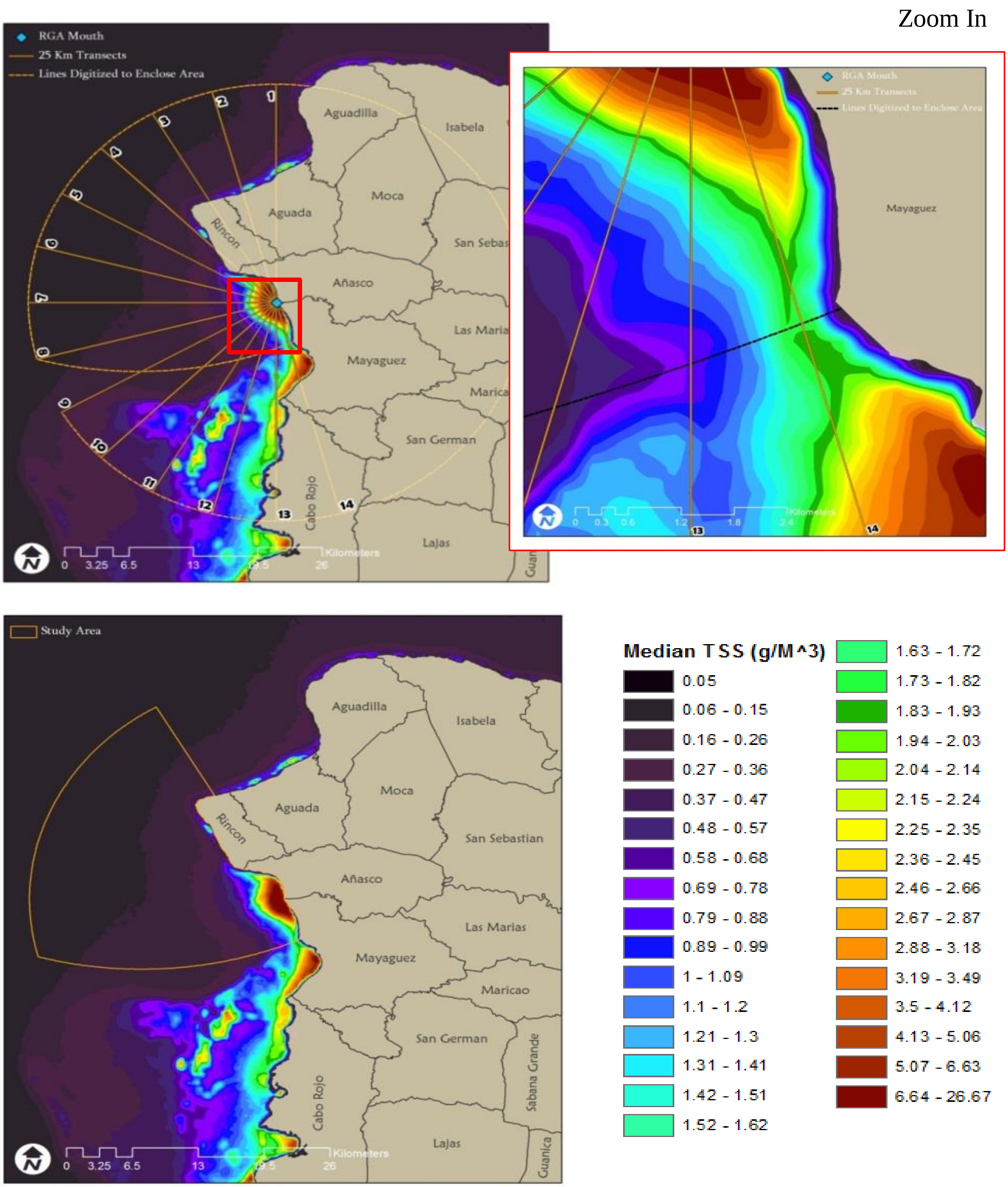
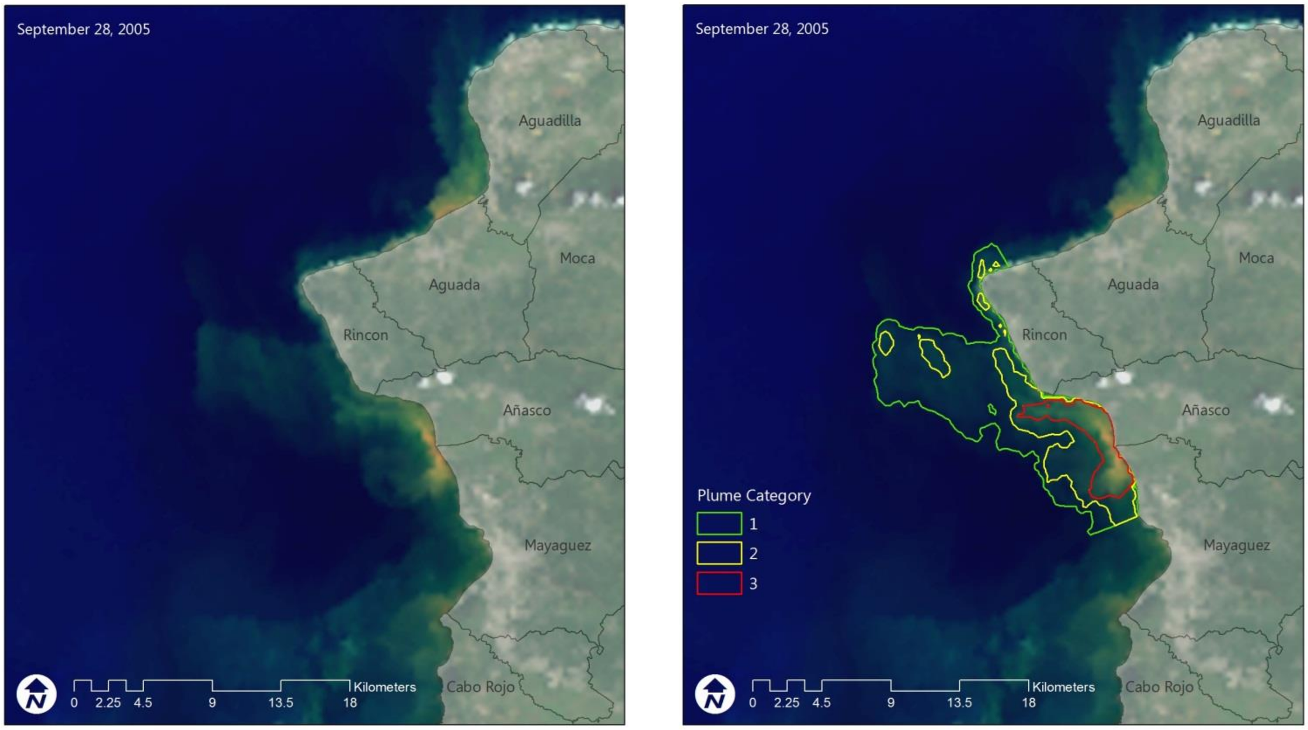
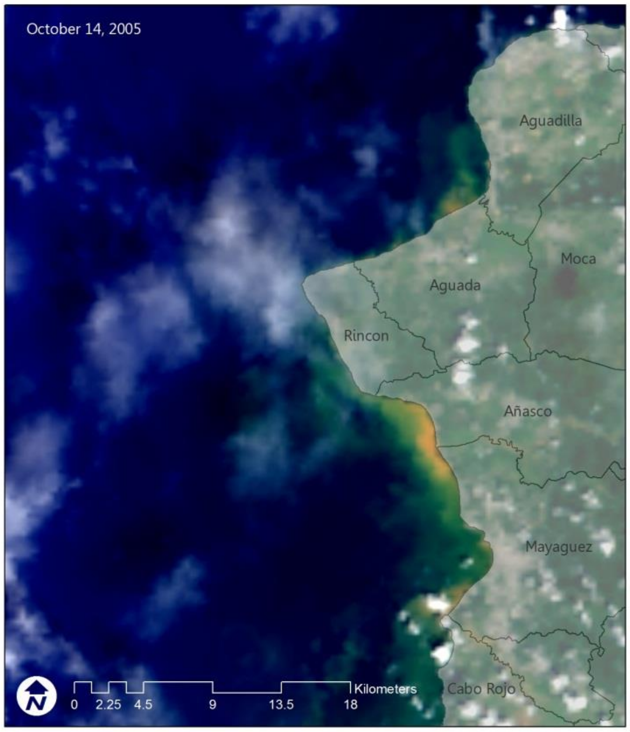


Figure 1. *Visual description of geographic features considered to define the study area*

Figure 2. Comparison of plumes as observed in MERIS true color images and outlined areas defined using the plume mapping model

High Flow Events

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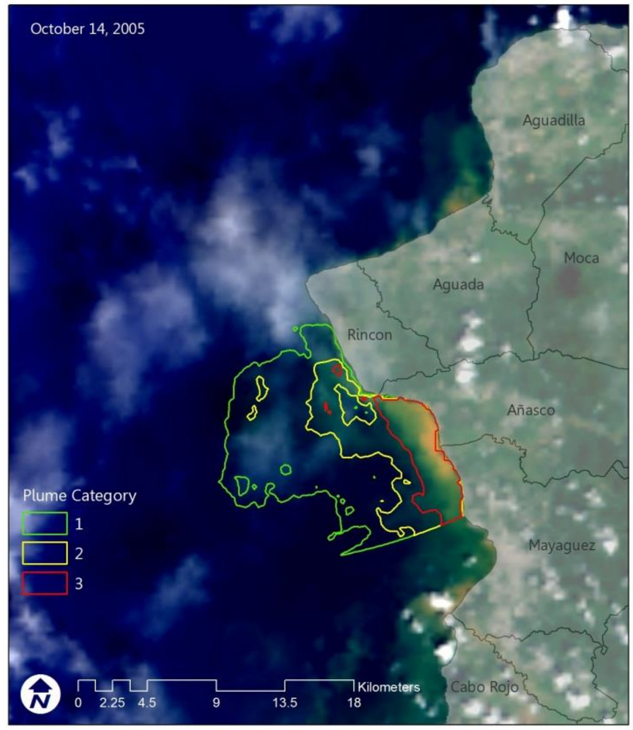
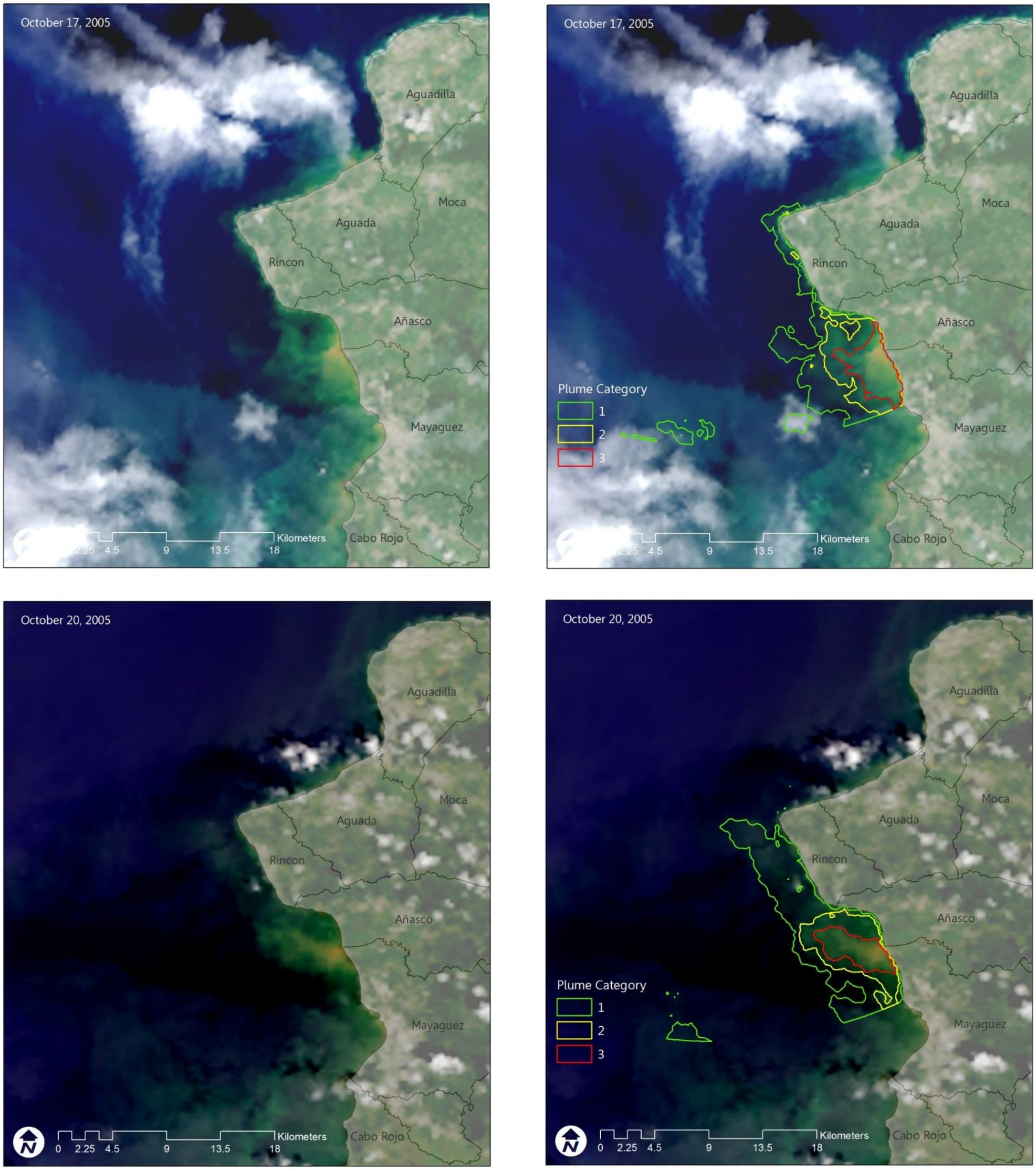
Aguadilla
Moca
Aguada
Rincon
Añasco
Mayaguez
Cabo Rojo
0 2.25 4.5 9 13.5 18
Kilometers


October 14, 2005
Aguadilla
Moca
Aguada
Rincon
Añasco
Mayaguez
Cabo Rojo
Plume Category
1
2
3
0 2.25 4.5 9 13.5 18
Kilometers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Rincon
Añasco
Mayaguez
Cabo Rojo
Kilometers
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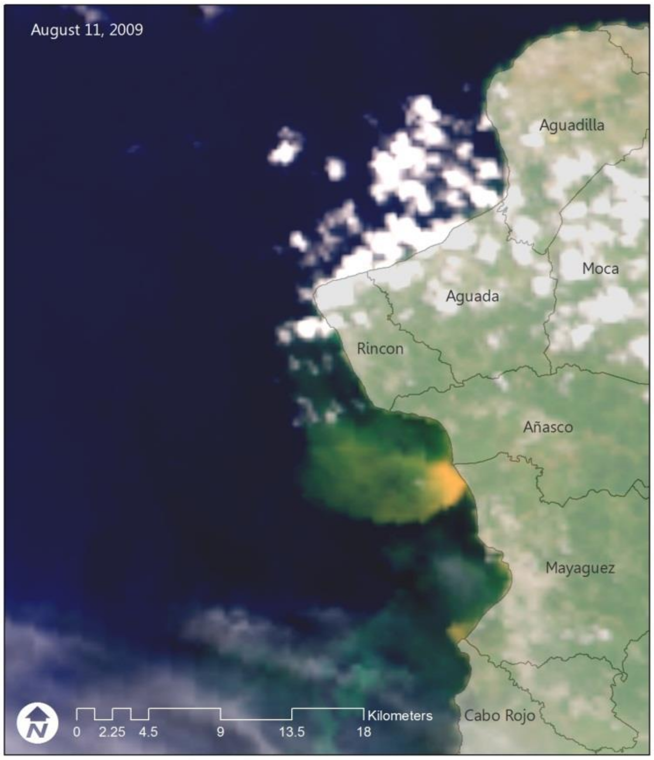
2
3
October 20, 2005
0 2.25 4.5 9 13.5 18
October 20, 2005
Plume Category
1
2
3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Rincon
Añasco
Mayaguez
Cabo Rojo
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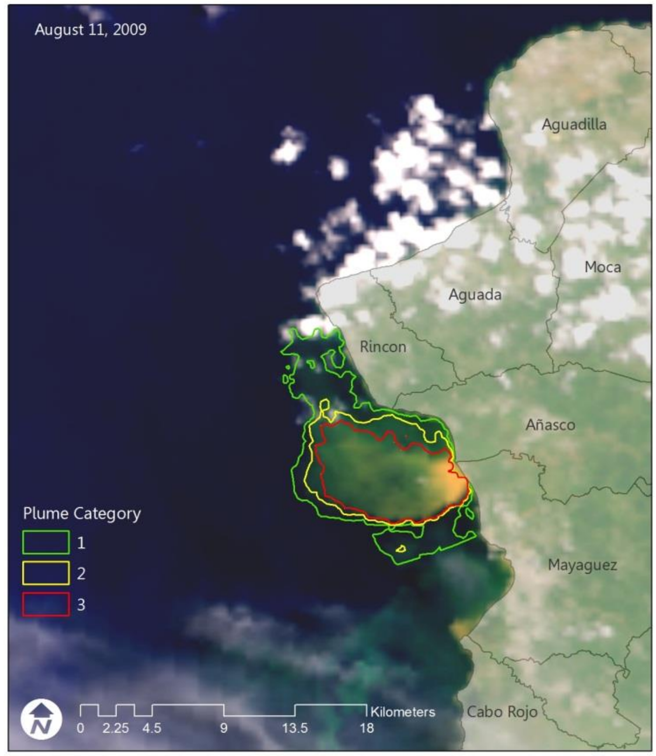
Kilometers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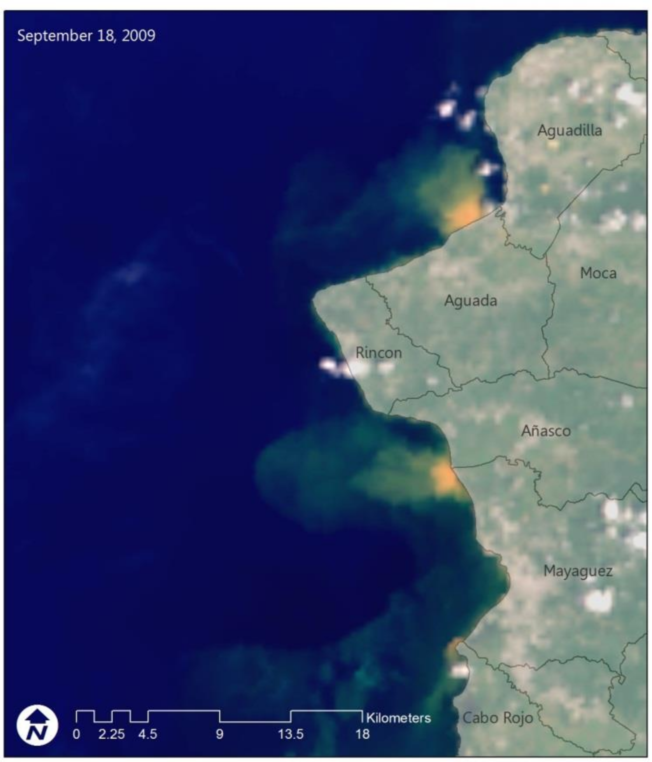
Kilometers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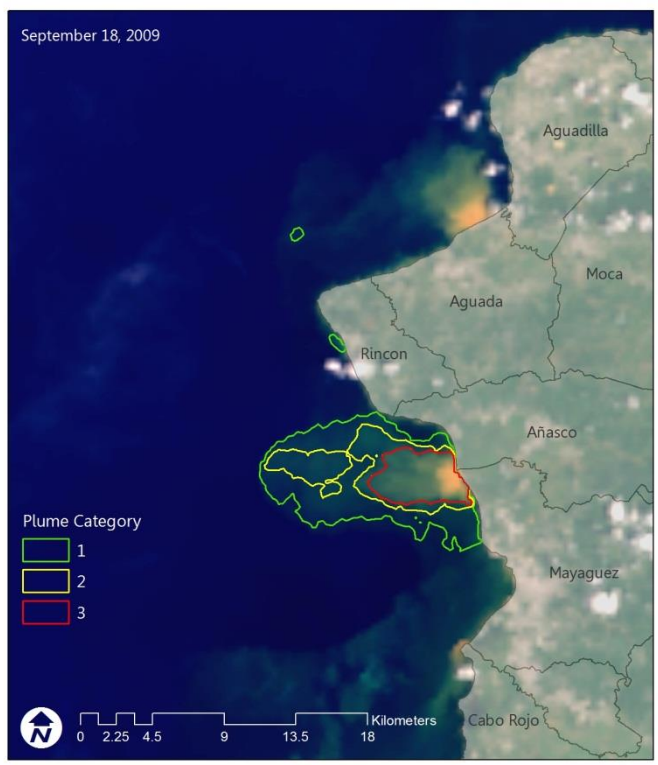
Kilometers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Mayaguez
Cabo Rojo
Plume Category
1
2
3
N
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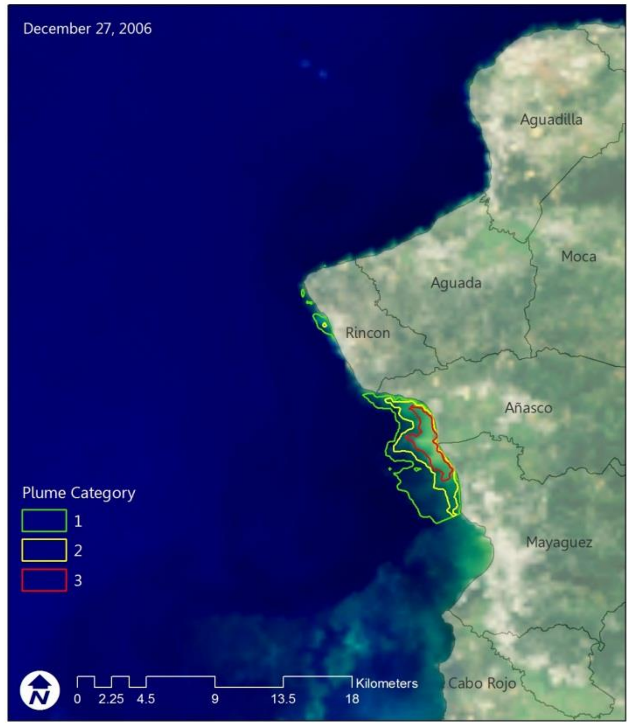
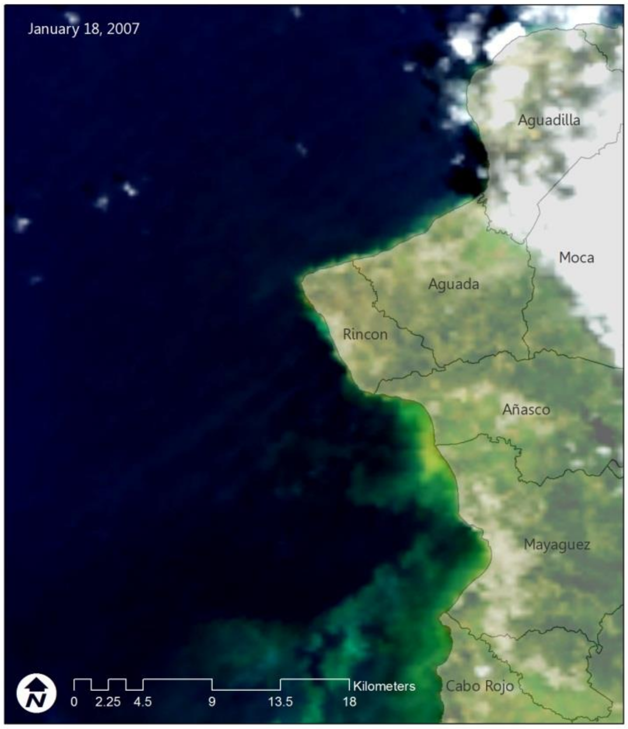
Kilometers

Low Flow Events

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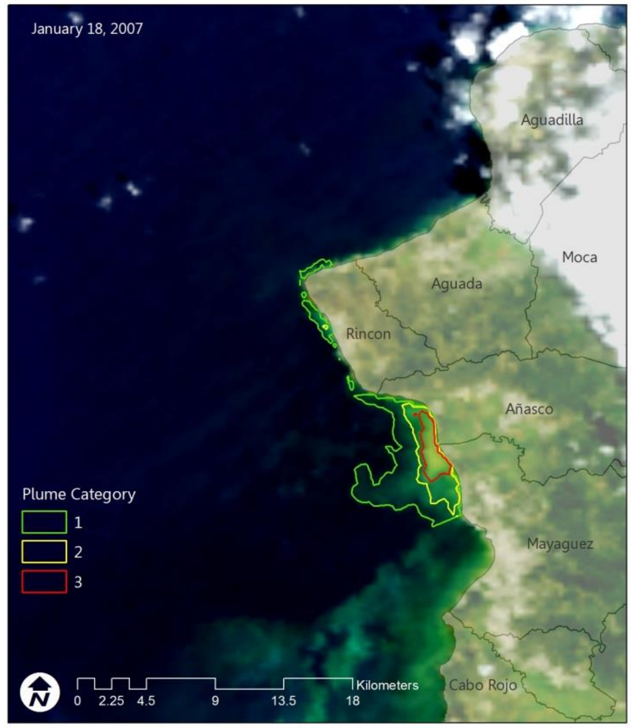
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Cabo Rojo
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1
2
3
Kilometers
0 2.25 4.5 9 13.5 18


January 31, 2007
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Moca
Aguada
Rincon
Añasco
Mayaguez
Cabo Rojo
Kilometers
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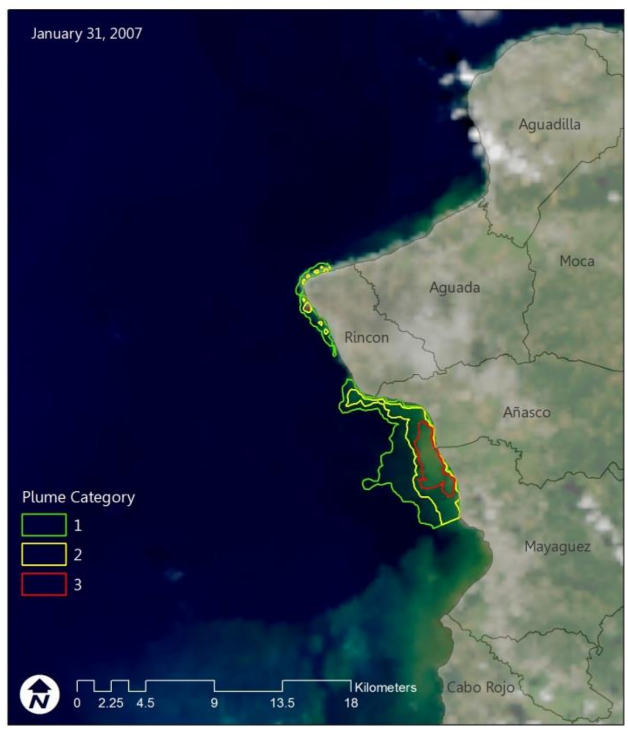
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Cabo Rojo
Plume Category
1
2
3
Kilometers
0 2.25 4.5 9 13.5 18


March 07, 2007
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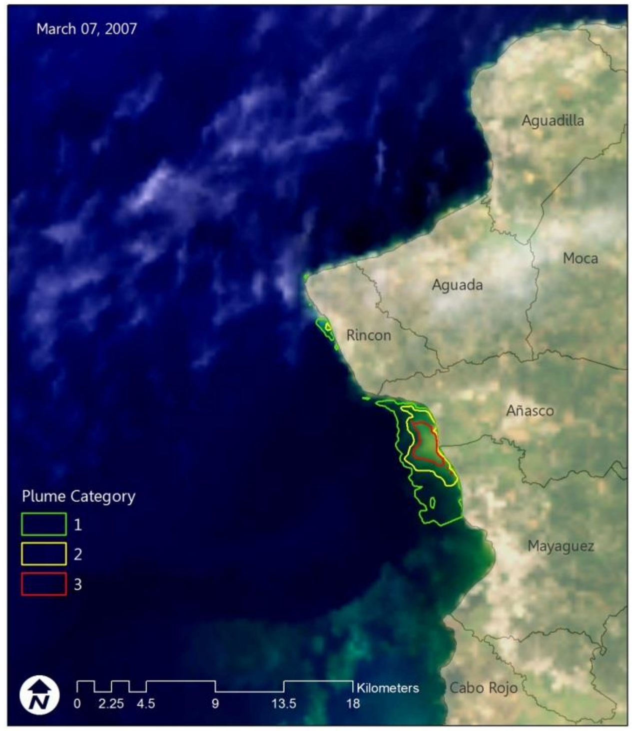
Aguada
Rincon
Añasco
Mayaguez
Cabo Rojo
0 2.25 4.5 9 13.5 18 Kilometers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1
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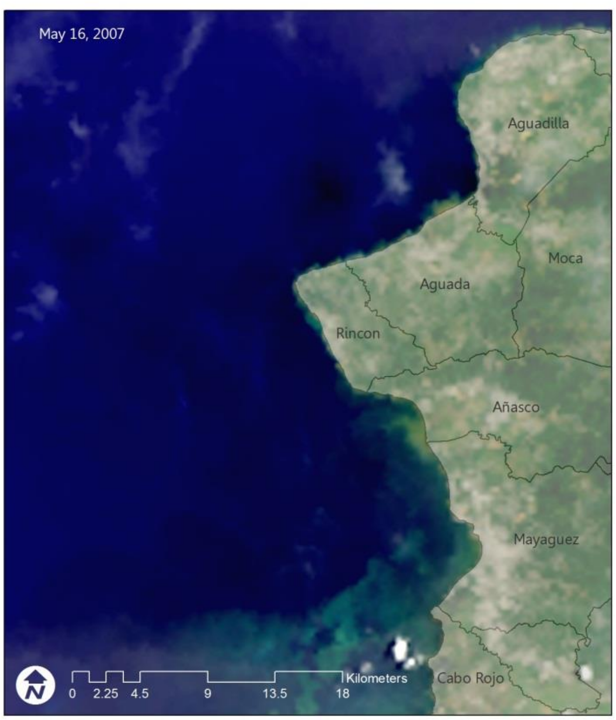
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Rincon
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Mayaguez
Cabo Rojo
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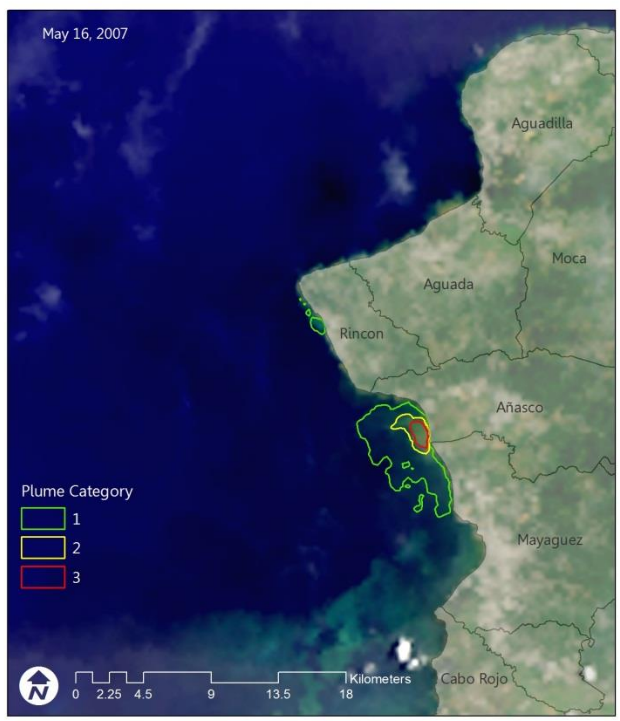
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Añasco
Mayaguez
Cabo Rojo
Plume Category
1
2
3
0 2.25 4.5 9 13.5 18 Kilometers


February 20, 2008
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Añasco
Mayaguez
Cabo Rojo
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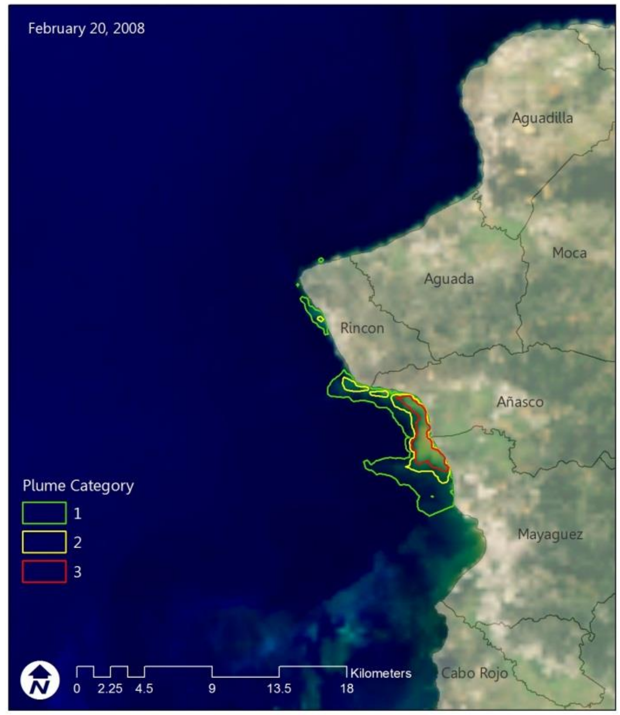
Kilometers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Moca
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Mayaguez
Cabo Rojo
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2
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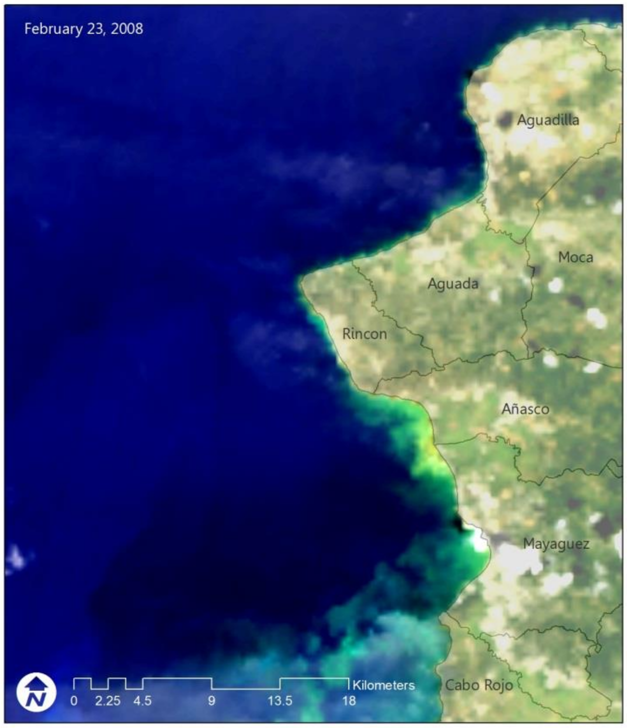
Kilometers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Cabo Rojo
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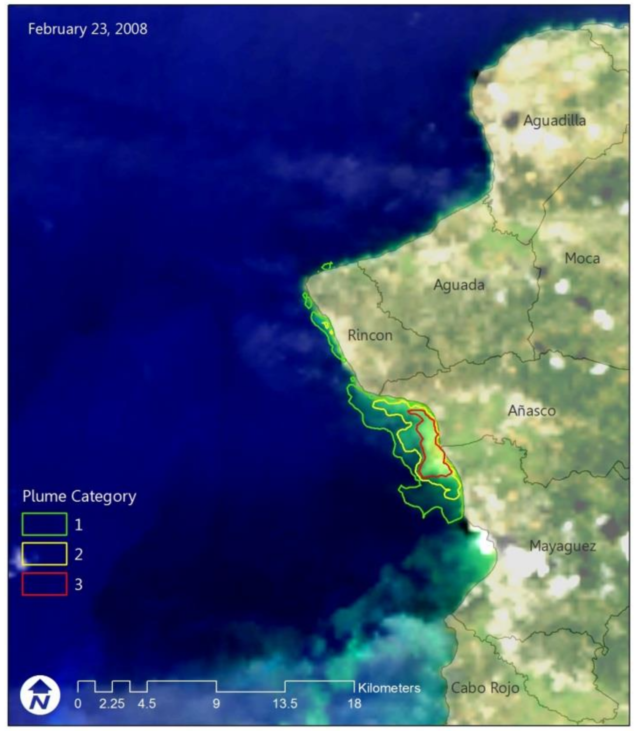
Kilometers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Moca
Aguada
Rincon
Añasco
Mayaguez
Cabo Rojo
Plume Category
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2
3
0 2.25 4.5 9 13.5 18
Kilometers

Figure 3. *Model builder layout view showing data process and flow to estimate the extension of the river plume.*

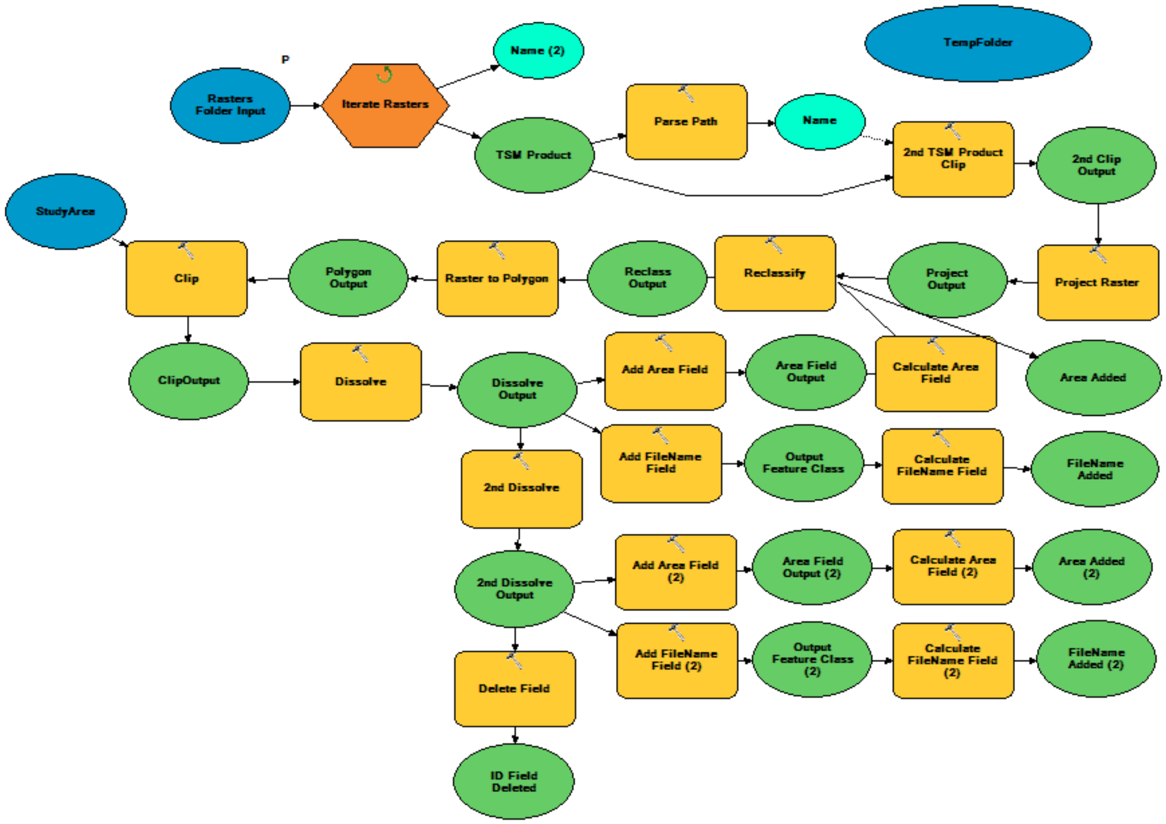

Table 2. *TSS value range used during the delimitation and classification of river plumes*

TSS Values (g/m^3)	Plume Category
0.000 - 0.720	No Plume
0.721 - 2.670	1
2.671 - 7.110	2
7.111 - 60.000	3

Figure 4. *Model builder layout view showing the data process and flow used for the plume direction analysis*