ESTIMATION OF SURFACE SUSPENDED SEDIMENT CONCENTRATION IN THE MAGDALENA RIVER MOUTH (COLOMBIA) USING MODIS IMAGES

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ABSTRACT – Traditional field methods used to monitor river's superficial physicochemical characteristics have limitations over large areas. Many studies have used remote sensing to monitor surface suspended sediment distribution. The Magdalena River is the main contributor of freshwater and sediments to the Caribbean Sea. The fluvial inputs of the Magdalena River are 10,287 m^3s^{-1} at high flow rates and 4,068 m^3s^{-1} at low flow rates, and sediment transportation has been considered one of the largest in the world ($142x10^6$ ty^{-1} of suspended sediments). Here we developed a regional algorithm to estimate the surface suspended sediment concentration in the Magdalena River mouth using MODIS images. We analyzed monthly average surface suspended sediment concentration data for the period 2003-2017. Satellite images were calibrated with *in situ* measurements of surface suspended sediment concentrations in the study area. Results confirm that surface suspended sediment concentrations are much higher than data reported from previous studies carried out in the area. Concentrations data range from 2000 to 5000 mgL^{-1} in the Magdalena river, from 500 to 3000 mgL^{-1} in the estuary (Bocas de Ceniza) and ≤200 mgL^{-1} along the adjacent coastal zone (Caribbean Sea). During the dry season the highest surface sediment concentrations were obtained in the river and in the estuary. For this time period the Magdalena River plume moves from Bocas de Cenizas towards the south-west along the coast with the littoral drift. Our results emphasize the importance of movement of sediments from the Magdalena River to the Caribbean Sea. This is an important process in the biogeochemical functioning of estuarine systems and even more in highly turbid estuaries, where there is a marked variability in the surface distribution of sediments.

Keywords – Surface suspended sediment concentration, remote sensing, Magdalena River.

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1 - INTRODUCTION

River discharges lead to the formation of buoyant plumes (Osadchiev et al., 2017). These river plumes play an important role in the physical, chemical and ecological dynamics of coastal zones, due to their transport freshwater, nutrients and sediments from the river mouth to the sea (Fernández-Nóvoa et al., 2015). Thus, river plumes are a key element in the delivery and dispersal of terrestrial sediments (Wright & Nittrouer, 1995). In high discharge rivers, transporting high sediment loads, the dispersal of sediments becomes particularly complex. However, the physical and geochemical dynamics of high-discharge and turbid estuaries, with large variations, have been poorly studied. The Magdalena River delta is the most important coastal marine ecosystems in Colombia and one of the most important in the world. It has large fluvial inputs of water (10,287 m^3s^{-1} and 4,068 m^3s^{-1} at high and low streamflow, respectively) and suspended sediments (142 x 10^6 ty^{-1} of suspended sediments) to the Caribbean Sea, considered one of the largest in the world (Restrepo et al., 2017). However, there is no detailed information on the variability patterns of the surface suspended sediment concentration in the Magdalena River mouth (e.g. Sediment plume), where large concentrations gradients are expected (Restrepo et al., 2018). Available database is scarce and disperse, exhibiting low spatial and temporal coverage (e.g. INVEMAR, 2017; Restrepo et al., 2018).

Several research have documented advances in the use of remote sensing techniques for water quality studies and their applications to coastal ecosystem management (Qing et al., 2013; Chen et al., 2015; Kim et al., 2017). Particularly, recent advancements of remote sensing technologies have provided the capability to characterize the surface suspended sediment concentration in aquatic environments (e.g. Park and Latrubesse, 2014; Espinoza-Villar et al., 2018). Remote sensing techniques have been used in the Colombian Caribbean to determine the extent of the sediment plume in the Canal del Dique, a distributary of the Magdalena River (Moreno-Madriñan et al., 2015; Restrepo et al., 2016). Moreno-Madriñan et al. (2015) did not performed calibration procedures; whilst Restrepo et al., (2016) employed *in-situ* sediment measurements obtained in the Rosario Islands, the Bay of Cartagena and the Canal del Dique for performing the satellite images calibration. However, these environments are less turbid than the Magdalena River estuarine system (Lonin et al., 2004).

In this study, we develop a regional algorithm to estimate the surface suspended sediment concentration in the Magdalena River estuary using MODIS images. Specifically, the study aims to delimit the turbid plume defining concentrations threshold and using different geometrical properties; to determine the spatio-temporal variability of the suspended sediment concentration; and to determine the factors controlling this variability.

2 - METHODOLOGY

2.1 - Study Area

The Magdalena River is located in Northwestern South America, Colombia (Figure 1). At this zone, the Caribbean Current dominates the surface ocean currents (Andrade, 2001). The Magdalena delta is classified as mixed domain, influenced by fluvial inputs and waves (Restrepo et al., 2016). The fluvial flux of the Magdalena River is considered as the main source of sediments towards the Caribbean Sea (Restrepo et al., 2016). The delta receives, on average, 142 x 10^6 tyr^{-1} of suspended sediments (Restrepo et al., 2017). The sediments of the river are mainly made up of very fine sands - coarse silt (d_{50}=70.6 m) (Alvarado, 2008); whereas sediment concentration in the river mouth can reach up to 10,000 mgL^{-1} (Restrepo et al., 2018). However, these physical parameters undergo a large seasonal variability. The Magdalena river drains to the Bocas de Ceniza estuary 10,287 m^3s^{-1} in high streamflows and 4,068 m^3s^{-1} in low streamflows (Higgins et al., 2016). In addition, during the low streamflow season, which coincides with the dry season, the trade winds intensify, generating high-energy waves coming predominantly from the Northeast (Andrade, 2001). Thus, the Magdalena River mouth is a tropical system with high river discharges and turbidity, experiencing large seasonal variability.

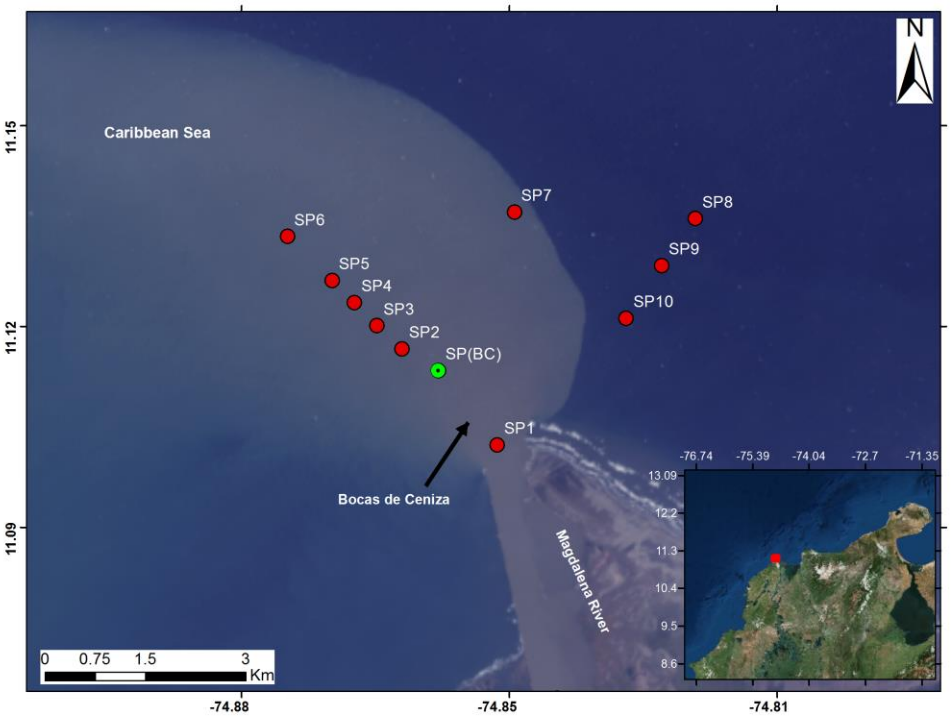

Figure 1. Magdalena River mouth. Red points were used for the satellite images calibration. Green point was used as a control point (BC=Bocas de Ceniza) (source: own authorship).

2.2 - Remote Sensing Data

Remote sensing was used as the tool to obtain information on surface suspended sediment concentration in the Magdalena River mouth for the 2003-2017 period. MODIS-Aqua data was obtained in HDF format from the NASA Ocean Color website (http://oceancolor.gsfc.nasa.gov) as composite images (8-day product) MYD09Q1. The pixel size is 250 m. These images provide an estimate of the surface spectral reflectance of Aqua MODIS Bands 1-2 and are corrected for atmospheric conditions such as gasses, aerosols and Rayleigh scattering. With the composite images, monthly images were obtained.

2.3 - Field Campaigns and Hydrometereological Information

A sampling campaign in the Magdalena River mouth was carried out in November 2017. The suspended sediment concentration was measured using a OBS 3A in the points shows in the Figure 1. Also, hydro-meteorological information was collected from the study area, monthly winds which were discharged from WaveWatch III (http://polar.ncep.noaa.gov), monthly flows discharged from the station closest to the mouth (Calamar approx. 100 km) (IDEAM-Colombia), and monthly currents discharged from Hybrid Coordinate Ocean Model (https://hycom.org).

2.4 - Calibration Images and Information Analysis

Regression analysis was applied to determine relations between the surface suspended sediment concentration and the reflectances (bands 1 and 2). Statisticians (e.g. RMSE half-square error, R^2, p-value) were used to identify the best fitted algorithm (Wu et al., 2014). ENVI and ArcGIS software were used for image processing.

The information obtained from satellite images and hydrometereological information collected was analyzed to (1) detect and quantify trends in historical series (2003-2017) and identify patterns of variability, (2) delimit the turbid plume of the Magdalena River and (3) to establish associations between the hydro-meteorological characteristics of the area and the suspended sediment concentrations. For the delimitation of the extent of the turbid plume, a turbid threshold was defined and different geometric properties of the turbid plume (area, perimeter and shape coefficients) were evaluated (Fernandez-Nóvoa et al., 2015).

3 - RESULTS AND DISCUSION

The satellite images were calibrated with in situ measurements (10 sampling points) of the surface suspended sediment (Figure 1). Figure 2 shows the dispersion diagrams of the Reflectance values for each band (B1 and B2) with the in situ values of the surface suspended sediment concentration. In situ values had to be transformed, using logarithm. Overall, 25 algorithms were obtained using only band 1 or only band 2, combining the reflectance values of bands 1 and 2, establishing relationships between the bands and exploring polynomial relationships.

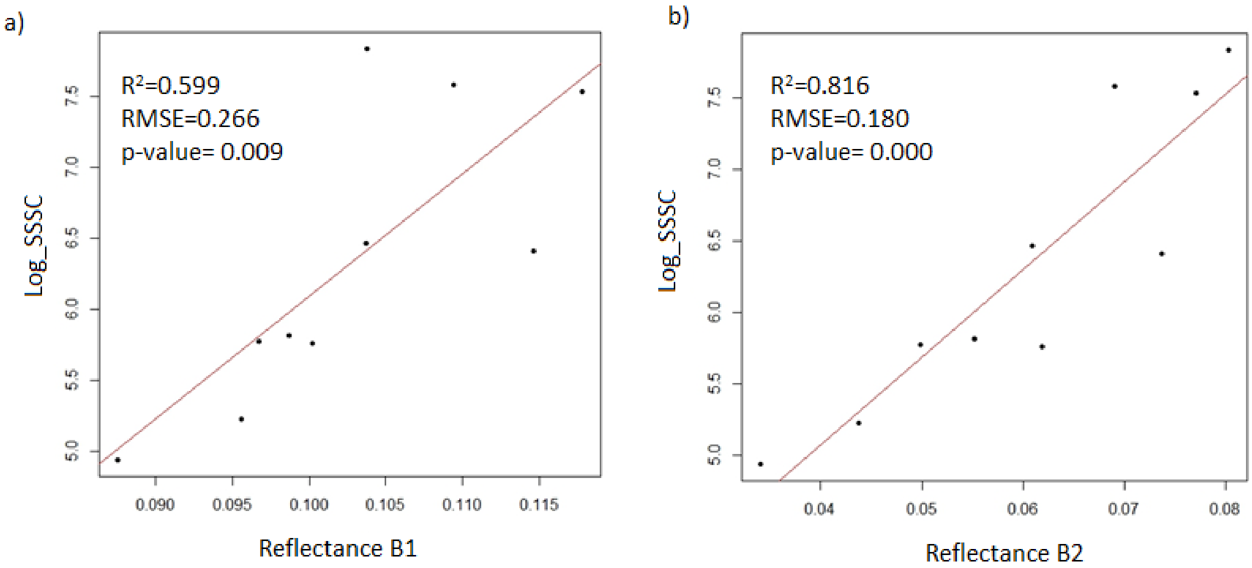

Figure 2. Relationship between reflectance and in situ measurements of surface suspended sediment concentration logarithm (SSSC) a) Reflectance B1 b) Reflectance B2 (source: own authorship).

Table 1 shows several algorithms obtained and the calculated statisticians used to identify the best fitted algorithm. The best fitted algorithm was Log SSSC = 2.03 – 2.0 (RB1) + 238.7 $(RB2)^2$. Where RB1 is reflectance of band 1, and RB2 is reflectance of band 2. Restrepo et al., 2016 used an algorithm obtained from the linear relationship between the reflectance of band 1 and the surface suspended sediments concentration (R^2=0.78), for to estimated surface suspended sediment concentration in the Magdalena River and Canal del Dique channel.

Table 1 – Several regional algorithms obtained to estimate the surface suspended sediment concentration

Algorithm	R^2	RMSE	p-value
Log SSSC = -1.11 + 37.53 (RB1)	0.599	0.266	0.009
Log SSSC = 1.135 + 26.67 (RB2)	0.816	0.180	0.000
Log SSSC = 0.849 + 178.6 $(RB1)^2$	0.583	0.271	0.003
Log SSSC = 1.861 + 229.8 $(RB2)^2$	0.831	0.173	0.000
Log SSSC = 2.03 – 2.0 (RB1) + 238.7 $(RB2)^2$	0.832	0.172	0.002
Log SSSC = 1.197 – 15.2 $(RB1)^2$ + 28.33 (RB2)	0.817	0.180	0.003
Log SSSC= 0.032 + 16.64 (RB1 + RB2)	0.775	0.199	0.001

The relation between the reflectance of bands 1 and 2 with the surface suspended sediment concentration is usually non-linear, especially in rivers with high sediment concentrations, and where the size, color and shape of the particles considerably varies (Ondrusek et al., 2012). In this sense, the polynomial relation allows to improve the adjustment in the prediction of the surface suspended sediment concentration.

The surface suspended sediment concentration was estimated monthly for 2017. Figure 3 shows the surface suspended sediment concentration in the Magdalena River mouth for February (dry season) and November (wet season). Generally, the concentrations showed a wide range, from 2000 to 5000 mgL^{-1} in the Magdalena river, 500 - 3000 mgL^{-1} in the estuary and <200 mgL^{-1} along the adjacent coastal zone. In dry season, the Magdalena River plume advances from Bocas de Cenizas towards the south-west along the coast with the littoral drift, confirming what described by Restrepo et al. (2006). In this sense, the force of the input of the river to the mouth could determine the direction of the turbid plume.

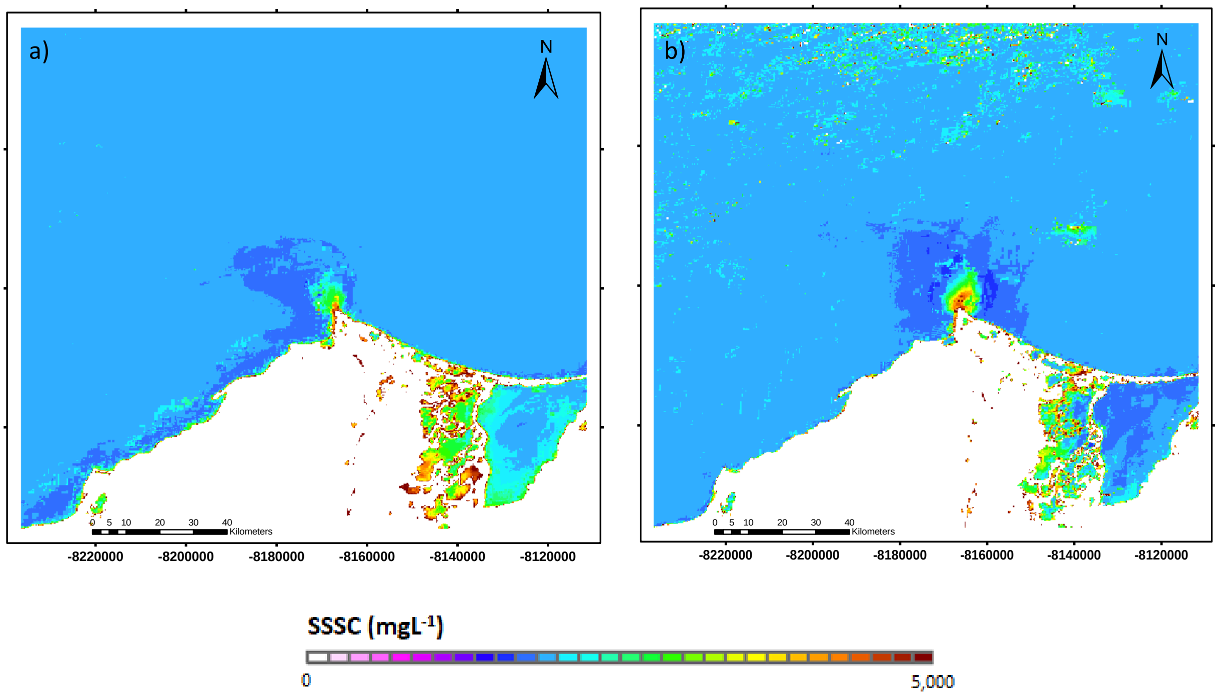

Figure 2. Surface suspended sediment concentration in the Magdalena River mouth a) February 2017, b) November 2017 (source: own authorship).

The surface suspended sediment concentrations are much higher than previous works carried out in the same study area (e.g. INVEMAR, 2017; Restrepo et al., 2016). Figure 3 shows the surface suspended sediment concentration in the control point (BC) and the monthly streamflows for the year 2017. The streamflows vary between 5000-13000 m^3s^{-1}. Higher surface suspended sediment concentrations were observed in the rising stage and maximum discharge.

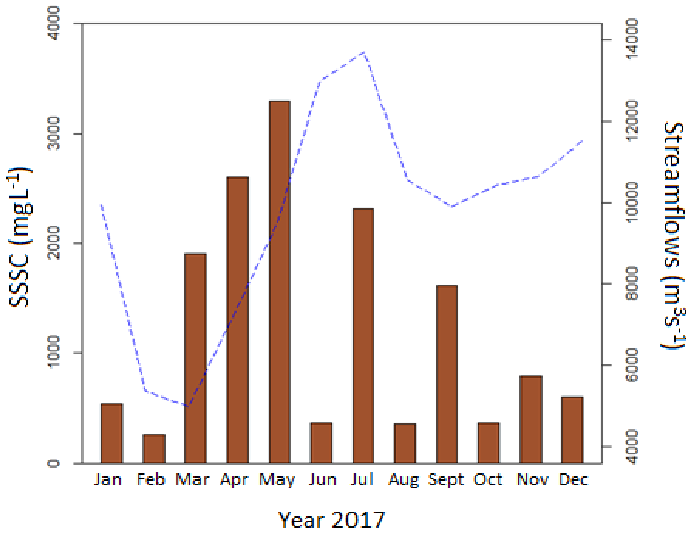

Figure 3. Bars correspond to surface suspended sediment concentration in the control point (BC) and line is the Magdalena River streamflows (source: own authorship).

Finally, the surface suspended sediment concentration from 2003-2017 will be estimated, with the purpose of 1) detect and quantify trends in historical series and identify patterns of variability, 2) observe the influence of Magdalena River input into the characteristics of the coastal zone adjacent, and 3) delimit the turbid plume of the Magdalena River.

4 - CONCLUSIONES

The polynomial relation between the surface suspended sediment concentration and the reflectance of MODIS images was established. A regional algorithm was developed for to determine the surface suspended sediment concentration at the Magdalena River mouth. A good correlation (R^2 =0.832; polynomial regression) was obtained between the reflectances (band 1 and 2) values and in situ measurements of surface suspended sediment concentration. In this sense, remote sensing can be used to analyze spatio-temporal patterns of surface suspended sediment concentration in deltas and estuaries.

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