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Coral reefs chronically exposed to river sediment plumes in the southwestern Caribbean: Rosario Islands, Colombia

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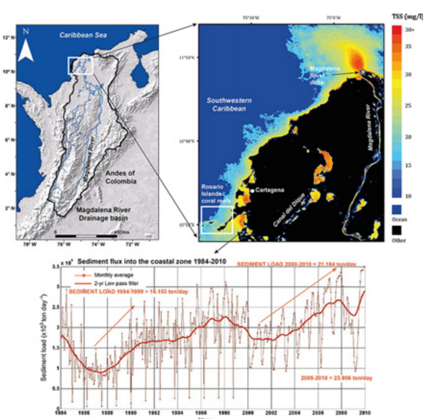
HIGHLIGHTS

- Results emphasize the importance of dispersion of turbid plumes on coral reefs.
- Reefs were exposed to turbid waters between 19.6 and 47.8% of the time.
- Heavy metals in deposited sediments are above the ecologically accepted standards.
- The last decade witnessed stronger magnitudes in fluvial fluxes to the coast.
- Coral reef management in the region needs to mitigate land and marine stressors.

GRAPHICAL ABSTRACT



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ABSTRACT

Politicians do not acknowledge the devastating impacts riverine sediments can have on healthy coral reef ecosystems during environmental debates in Caribbean countries. Therefore, regional and/or local decision makers do not implement the necessary measures to reduce fluvial sediment fluxes on coral reefs. The Magdalena River, the main contributor of continental fluxes into the Caribbean Sea, delivers water and sediment fluxes into the Rosario Islands National Park, an important marine protected area in the southwestern Caribbean. Until now, there is no scientific consensus on the presence of sediment fluxes from the Magdalena River in the coral reefs of the Rosario Islands. Our hypothesis is that high sediment and freshwater inputs from the Magdalena have been present at higher acute levels during the last decade than previously thought, and that these runoff pulses are not flashy. We use in-situ calibrated MODIS satellite images to capture the spatiotemporal variability of the distribution of suspended sediment over the coral reefs. Furthermore, geochemical data are analyzed to detect associated sedimentation rates and pollutant dispersion into the coastal zone. Results confirm that turbidity levels have been much higher than previous values presented by national environmental authorities on coral reefs off Colombia over the last decade. During the 2003–2013-period most of the Total Suspended Sediments (TSS) values witnessed in the sampled regions were above 10 mg/l, a threshold value of turbidity for healthy coral reef waters. TSS concentrations throughout the analyzed time were up to 62.3 mg/l. Plume pulses were more pronounced during wet seasons of La Niña events in 2002–2003, 2007–2008, and 2009–2010. Reconstructed time series of

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MODIS TSS indicates that coral reef waters were exposed to river plumes between 19.6 and 47.8% of the entire period of analysis (2000 − 2013). Further analyses of time series of water discharge and sediment load into the coastal zone during the last two decades show temporal increases in water discharge and sediment load of 28% and 48%, respectively. ^{210}Pb dating results from two cores indicate sedimentation rates of ~0.75 cm/y of continentally exported clastic muddy sediments that are being deposited on the carbonatic shelf. The cores contain sediments with heavy metals and their concentrations are frequently above the ecologically accepted standards. Overall, the last decade has witnessed stronger magnitudes in fluvial fluxes to the coastal region, which probably coincide with associated declines in healthy coral cover and water quality. Our results emphasize the importance of local stressors, such as runoff and dispersion of turbid plumes, as opposed to ocean warming, disease and hurricanes, which have played a larger role on other coral reefs in the Caribbean. Coral reef management across the southwestern Caribbean, a coastal region influenced by continental fluxes of numerous rivers flowing from the Andes, may only be effective when land and marine-based stressors are simultaneously mitigated.

1. Introduction

Anthropogenically enhanced delivery of sediments and other land-based sources of pollution represent well-recognized threats to near-shore coral reef communities worldwide (Ramos-Scharrón et al., 2015; Wolanski et al., 2004). The role of terrigenous sediment in controlling the occurrence of coral reefs has been globally recognized. Sediments have inhibitive effects on reef communities and the sedimentation processes, including various associations between substrate type, turbidity and light availability, affecting coral distributions on all scales from local depth restrictions to broad-scale biogeography (e.g. McLaughlin et al., 2003; Rogers, 1990; Wolanski et al., 2003).

In the Caribbean, water transparency steeply declined over the last 20 years at different locations from Guatemala to Honduras, and also at La Parguera in Puerto Rico (Jackson et al., 2014). The impact of changes in transparency are poorly understood for the Caribbean basins of Colombia and have been less studied for the Magdalena River (Gómez Giraldo et al., 2009; Moreno-Madriñán et al., 2015; Restrepo and Alvarado, 2011; Restrepo et al., 2006a) (Fig. 1). This river system is the main contributor of fluvial fluxes towards the Caribbean Sea (Restrepo

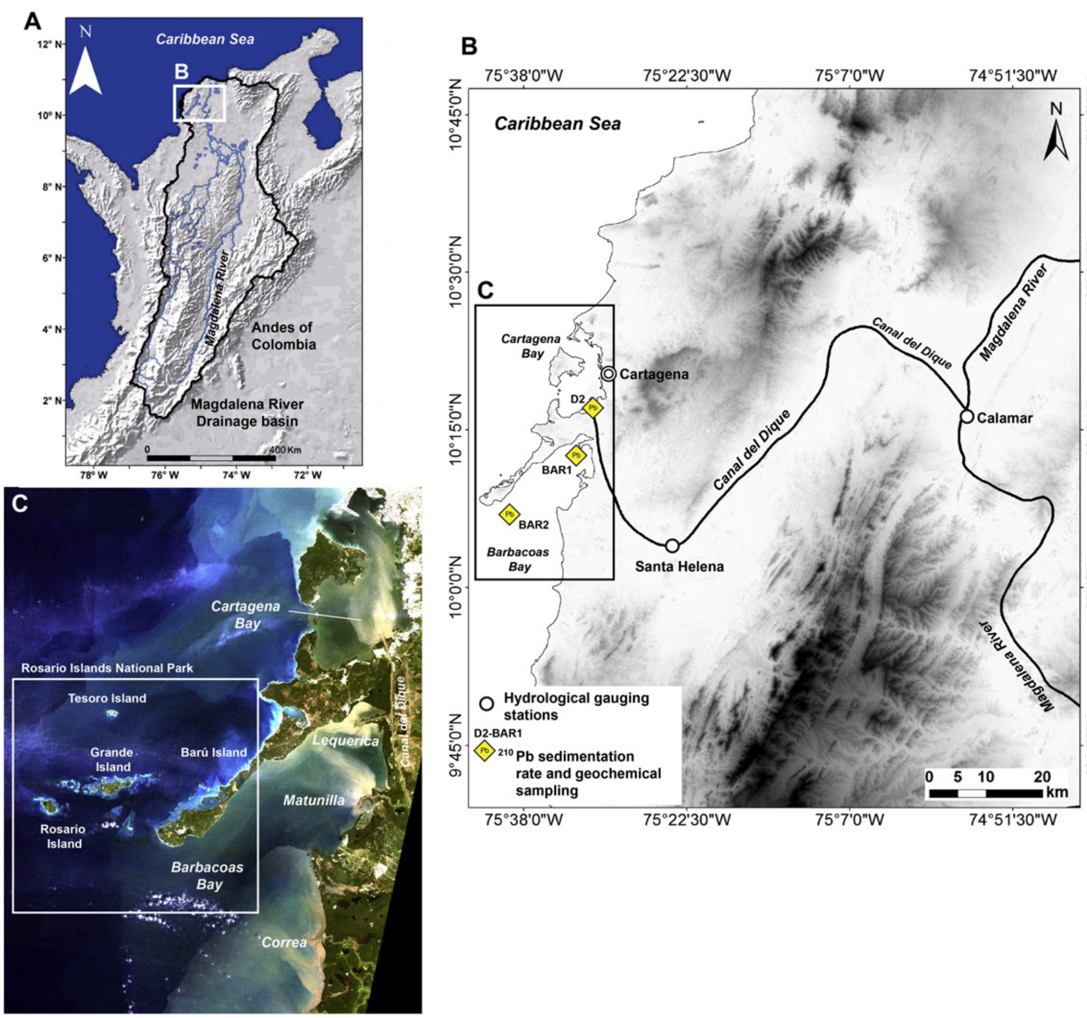

Fig. 1. (A) Location of the Magdalena drainage basin in the northern Andes. (B) Lower course of the Magdalena River and its distributary channel, the Canal del Dique, showing hydrological gauging stations at Calamar and Santa Helena, the Cartagena and Barbacoas Bays, and sediment core sampling places. (C) Satellite image showing the muddy plumes of the Canal del Dique in the Barbacoas and Cartagena Bays. The location of the Rosario Islands National Park is also shown.

and Kjerfve, 2000; Restrepo, 2008) and is probably the largest river system delivering continental fluxes to coral reef ecosystems (Restrepo and Alvarado, 2011).

There are not many scientific interpretations available for the depositional extents of fluvial sediments in the Caribbean. Coastal ecosystem processes under the influence of fluxes from the Andean rivers of Colombia are poorly understood due to insufficient data on pre-disturbance water quality or habitat status, the lack of data from undisturbed sites and inadequacies in the measurement of water-quality parameters. Only some studies have preliminarily addressed the connectivity between the fluxes from the Magdalena River and the coral reefs of the Rosario Islands National Park (Gómez Giraldo et al., 2009; Moreno-Madriñán et al., 2015; Restrepo and Alvarado, 2011; Restrepo et al., 2006b) (Fig. 1).

The first work, to our knowledge, in the region synthesizing data on water discharge, sediment load, and dissolved load of the Magdalena River, presented an initial interpretation of reef cover changes in relation to water discharge and sediment load from the Magdalena (Restrepo et al., 2006b). However, this study is limited in demonstrating the dispersion of turbid plumes into the coral reefs of the Rosario islands. Later, Gómez Giraldo et al. (2009) used a 3D ELCOM model to identify sediment loads and paths from the Barbacoas Bay (Fig. 1). The simulations showed that the circulation patterns in the bay were strongly influenced by the wind with the incoming rivers playing a minor role. Sediments from the Canal del Dique were simulated by a neutral tracer and the results indicated that the tracer reaches the Rosario islands sporadically in low concentrations.

Recently, Moreno-Madriñán et al. (2015) investigated the interannual temporal variability in water surface reflectance at the Rosario Islands and at the three main mouths of the Magdalena River. In their study, only MODIS images 2001–2013 from the January–March interval were processed, a seasonal period that corresponds to dry conditions in the Magdalena basin and low fluvial fluxes into the coastal zone (Restrepo and Kjerfve, 2000; Restrepo, 2008). In addition, the results in terms of reflectance failed to present levels of water turbidity in the Rosario Islands due to the lack of field calibration with total suspended sediment concentration (TSS). In general, this work by Moreno-Madriñán et al. (2015) does not capture the behavior of fluvial plumes in terms of TSS and, additionally, misses seasonal variations during medium-high discharge conditions from April to November. Even though the above studies presented valid approaches to identifying the presence of land based suspended sediments in the Rosario Islands, all lacked measurements and in-situ calibration of water quality in terms of TSS.

An important factor that has been identified to determine the risk of degradation of a coral reef system is its level of exposure (concentration and duration) to terrestrial fluxes. This exposure is spatially controlled by the downstream distance between a reef and the major sources of discharge (Petus et al., 2014). Also, the mean annual load from the source and dilution processes have strong effects on the coral degradation (Fabricius, 2005; West and Van Woesik, 2001). Many environmental surveys in the Rosario Islands (e.g. Alvarado-Chacón and Acosta, 2009; Alvarado, 2001; Restrepo and Alvarado, 2011; Restrepo et al., 2006b) suggest that coral reef formations in the area are exposed to increased levels of turbidity and sedimentation. Our hypothesis is that high sediment and freshwater inputs from the Canal del Dique into the coral reef waters of the Rosario Islands (Fig. 1) have been more constant during the last decade than previously thought and that these runoff pulses are not flashy. To test this hypothesis, this paper addresses the following questions: (1) what are the observed trends of fluvial fluxes of the Magdalena River and its distributary channel, the Canal del Dique, during the last three decades?, (2) have the sediment rich plumes of the Magdalena River and the Canal del Dique been constant and prolonged, and therefore could their impact be more significant?, and (3) can other geochemical proxies be used to support the dispersion of continental pollutants into the coral reef ecosystems?

One way to measure the influence of terrestrial runoff and sediment load on coral reefs and seagrasses is to analyze data of suspended sediments in waters overlying these ecosystems (Gilmour, 1999; Larcombe et al., 1995; Petus et al., 2014). For example, the use of remotely-sensed data in combination with in-situ sampling of water quality parameters during river plume events in the Great Barrier Reef have improved our knowledge about the composition, occurrence and extension of river plumes in coral reef waters (Devlin et al., 2012a). Supervised classifications of spectrally-enhanced quasi-true color MODIS images have been proposed by Álvarez-Romero et al. (2013) and Petus et al. (2014) to map river plumes in coral reef ecosystems. Alternative methods have used Colored Dissolved Organic Matter as an optically active constituent of river plumes, as well as combinations of Level 2 (L2) products derived from MODIS satellite images (Devlin et al., 2012a) to delineate plume surface boundaries (Schroeder et al., 2012). These methods, in combination with pollutant loads, have been used to estimate acute or constant exposure of coastal marine ecosystems to land-based pollutants (Álvarez-Romero et al., 2013; Devlin et al., 2012a; Devlin et al., 2012b; Maughan and Brodie, 2009; Petus et al., 2014). In this study, we use MODIS satellite images from both MODIS sensors onboard Terra and Aqua at 250-m spatial resolution to capture the spatiotemporal variability of surficial sediment distribution over the regional coastal zone of Cartagena and associated coral reefs of the Rosario Islands. Furthermore, geochemical data are analyzed to detect associated sedimentation rates and pollutant dispersion into the coastal zone.

The hydrologic cycle and associated fluxes of terrestrial sediment are among the environmental factors that have been dramatically altered by human intervention (Syvitski et al., 2005). Better understanding the environmental and oceanographic consequences of human induced alterations on land will form the base to establish an *action – consequences* knowledge system (McLaughlin et al., 2003; Wilkinson, 1999). Assessing connections between continental fluxes and the causes of coastal ecosystem deterioration (i.e. coral mortality), necessarily addresses the net combined effects of fluvial discharge-related stressors (Restrepo, 2008; Restrepo et al., 2006a; Wolanski et al., 2004). Understanding the spatial extent, frequency of occurrence, magnitudes and ecological impacts of land-based sediments and pollutants delivered by rivers is essential to drive catchment management actions (Petus et al., 2014). The spatial and temporal analyses of river plumes and tracers of sedimentation and pollutants presented here may be further used to develop water turbidity maps and provide easily replicable, regional-scale information to drainage-coastal decision makers about plume risk assessment, mitigation and management.

2. Materials and methods

2.1. Study area

The Magdalena River is the largest river system of Colombia with a length of 1612 km and originates from the Magdalena lagoon at an elevation of 3685 m. The drainage basin area covers 257,438 km^2, 24% of the Colombian territory, and occupies a considerable portion of the Colombian Andes (Fig. 1). The Magdalena River discharges into the southwestern Caribbean and forms a 1690 km^2 triangular delta (Coleman, 1976). The delta plain consists of alluvial plains, marginal lagoon systems, and beach ridges. It also comprises the largest estuarine lagoon complex in Colombia known as Ciénaga Grande de Santa Marta, a lagoonal complex surrounded almost entirely by mangrove forests (Vernette, 1985).

The Magdalena River flows towards the Caribbean through the Canal del Dique, a 114-km-long man-made distributary channel from the Magdalena River at Calamar to Barbacoas and Cartagena Bays (Fig. 1). Since the late 1920s, the government of Colombia has dredged the Canal del Dique. Because of increased sedimentation in Cartagena Bay during the 1940s, new channels were constructed from El Dique to Barbacoas Bay. Since then, the suspended sediment load has reached and impacted the Rosario Islands, a 145 km^2 offshore coral reef in Barbacoas Bay (Mogollón, 2013; Restrepo et al., 2006b), the major continental coral reef system in Colombia that belongs to the Colombian marine protected areas (Fig. 1).

2.2. Water discharge and sediment load

Data of water discharge (1940–2011) and suspended sediment load (1972–2011) in the Magdalena River from the downstream station at Calamar (Fig. 1) were obtained from Instituto de Hidrología, Meteorología y Estudios Ambientales, IDEAM. Calamar captures the combined processes of sediment transport and deposition for the whole Magdalena basin. Water discharges (1979–2010) and sediment loads (1984–2010) in the Canal del Dique at Santa Helena station (Fig. 1), were also obtained from IDEAM. Santa Helena represents the fluvial fluxes discharged into the Canal del Dique by the Magdalena River. Water discharge data are based on daily stage readings while sediment load estimates were derived from sediment concentrations measured by IDEAM-Uninorte (Alvarado, 2008).

To test temporal trends in fluvial fluxes into the coastal zone of Cartagena during the last three decades, a nonparametric Mann-Kendall (M-K) test was applied to detect trends of water discharge and sediment load for the Magdalena at Calamar and Canal del Dique at Santa Helena (Fig. 1). The Sen's slope, a non-parametric procedure for estimating the slope of trend in the sample of any N pair data, was used to test the trends in water discharge and sediment load. The sign of this slope estimator reflects data trend reflection, while its value indicates the steepness of the trend. In addition, this slope indicator is widely used to analyze the magnitude of discharge per unit time period or rate of change, by dividing the Sen's slope to mean stream flow (Kendall and Stuart, 1967; Kendall, 1955; Mann, 1945). We also applied a modified M-K test (Hamed and Rao, 1998) to avoid possible errors associated with positive autocorrelations in the analyzed sediment load series (Blain, 2013). The C values calculated with progressive and retrograde series are named C1 and C2, respectively. The intersection point of the two lines, C1 and C2 ($k = 1, 2 \ldots n$), located within the 95% confidence interval provides the beginning of a step change point within a time series. Assuming a normal distribution with a 95% confidence level, a M-K statistic of $C > 1.96$ indicates a significant increasing trend, while a value of $C < 1.96$ indicates a significant decreasing trend (Gao et al., 2015).

To identify patterns of discharge variability at various time scales, the Continuous Wavelet Transform (CWT) is used to examine the time series with generalized local base functions (i.e., mother wavelets) that were stretched and translated to both a frequency and time resolution (Restrepo et al., 2014; Torrence and Compo, 1998). This robust technique supports the evaluation of time series containing non-stationarities with different frequencies, providing a time-scale localization of a signal. Thus, the CWT, applied on monthly deseasonalized water discharge and sediment load at Calamar and Santa Helena, is used to estimate periodicities and variability patterns, as well as to distinguish temporal oscillations in water discharge and sediment load, identifying the intermittency of each time-scale process (Restrepo et al., 2014).

2.3. MODIS data and processing: calibration modeling, generating plume maps, and extracting TSS series

We utilized MODIS daily (MOD/MYD09GQ, L2) and 8-day composite (MOD/MYD09Q1, L3) data both from Terra and Aqua satellites at 250 m spatial resolution (Huete et al., 2002). These data are corrected for the effects of atmospheric gases and aerosols to yield surface reflectance at two bands: band 1 (620–670 nm) and band 2 (841–876 nm) (Vermote and Vermeulen, 1999). In particular, we used band 1 to map surface sediment plumes, which efficiently classifies different surface water types with distinct suspended sediment characteristics, and also estimate Total Suspended Sediments (TSS) concentrations (Park and Latrubesse, 2015). MODIS data were downloaded from the Land Processes Distributed Active Archive Center (USGS LPDAAC) file transfer protocol site for 16 years (2000–2015). Further series of steps on the image quality controls and reprojections followed methods described in detail by Park and Latrubesse (2014).

A relevant disturbance on coral reefs that is not well studied and understood in the Rosario Islands is that produced by the continental runoff from the Magdalena River and its distributary channel, Canal del Dique. In-situ data used in this study were collected as part of the Environmental Baseline of Barú Island (Restrepo and Correa, 2014). Sampling location was based on which outlets were expulsing turbid waters and the areal extent of the river plumes in the region. Thus, data were collected in a series of transects heading out from the outlets of the Canal del Dique at Cartagena and Barbacoas bays (Figs. 1 and 2) and towards the main direction of the turbid plumes. The collected TSS samples were sealed and sent to the Fluvial Sedimentology Lab at the University of Texas at Austin. Using 0.45 μm cellulose acetate membranes TSS samples were filtered and then dried to be weighted. For the post-sampling protocol details, see GEMS/WATER (1994). On the 268 total qualified surface reflectance data from the daily MODIS data centered on field measurements (Fig. 2), we derived a calibration model to predict surface sediment concentration as a function of surface reflectance. Consistency of the slopes of the calibration models throughout the sampling period (August to November) is first verified using analyses of covariance (Park and Latrubesse, 2014). Our empirically driven calibration model indicated statistical significance between surface reflectance and TSS at 99% confidence level with R^2 and root mean square error of 0.78 and 4.3 mg/l, respectively. We reported the robust standard error of the estimated coefficient to control inconsistent residuals (White, 1980) (Fig. 2).

Subsequently, we classified 1458 MODIS 8-day composite data between 2000 and 2015 into two classes: water and other (land, cloud/shade, sand bar and macrophytes) over a large area around Cartagena Bay. Then the daily data driven empirical model (Fig. 2) was applied to the water class of the 8-day composite data to generate TSS time

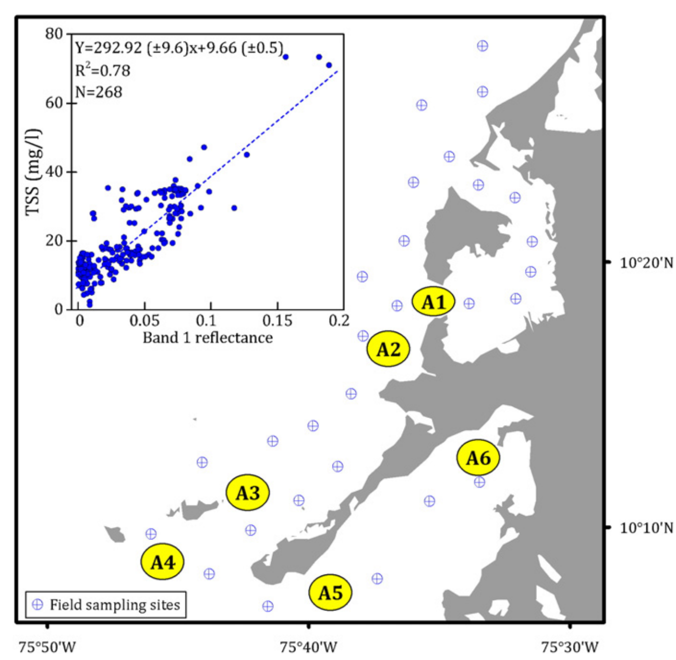

Fig. 2. Location of water quality sampling for the MODIS data calibration conducted during August, September and November in 2013. Yellow windows (A1–6) represent virtual gauge stations where we extracted TSS time series (2000–2013) from MODIS data. Inset graph indicates regression calibration model retrieved from field TSS and surface reflectance data from MODIS band 1.

series maps over 16 years. Effects from both algal blooms and algae cover on water surface reflectance are limited at MODIS band 1 (red, 620–670 mm) in this area. Measured Chlorophyll α concentration around the Rosario Islands ranged between 0.74 and 2.27 mg/m^3 during the field sampling campaigns in different seasons of 2014 and 2015 (Tosic et al., Forthcoming), which are considerably below the reported threshold value of Chlorophyll α concentration, i.e. 30 mg/m^3 that may interfere the surface reflectance at red band (Dogliotti et al., 2015). The measured values were also within the accepted background reference values used in comparative analysis of water quality (EPA, 2012). Furthermore at red band, high attenuation of the water column and sediment induced turbidity minimizes the reflectance contribution from the bottom, that remote sensing instrument typically records the surface reflectance from only first few inches of the water surface (Hu et al., 2004).

Unqualified pixels are interpolated using the Gaussian kernel local polynomial regression, which accounts for both the local and global TSS distribution patterns in the water surface (Park and Latrubesse, 2014). Within the water pixels, 'plume' was further classified from the 'ocean' by including pixels with TSS above 10 mg/l, which is a tolerance limit threshold of coral reefs for chronic suspended sediment concentration reported by Erftemeijer et al. (2012). To efficiently present the seasonal variations of the surface sediment concentrations within the Magdalena River plume, we illustrate 16-years (2000–2015) monthly averaged TSS maps throughout the hydrological year (Fig. 4). Finally, 14-years (2000–2013) TSS time series were extracted from MODIS data (at every 8 days interval) at six virtual gauge windows (A1–6) indicated in Fig. 2 to investigate the annual TSS deviation patterns (Fig. 5 and Table 3).

2.4. Geochemical data: sedimentation rates and tracers of pollutants

Changes in recent sedimentation rates are, in a first approximation, indicative of changes in deposition due to human and natural drivers (Bonachea et al., 2010). To compare the sedimentation rates with human activities altering sediment fluxes in the Magdalena River, we extracted three sediment cores at the lowest reach of the Canal del Dique. Hand-driven PVC tubes were used to extract two cores in the Canal del Dique and associated lagoon systems (Fig. 1). Cores were cut into 1 cm thick slices and dated using the ^{210}Pb method (Appleby and Oldfield, 1978; Appleby and Oldfield, 1983; Sanchez-Cabeza et al., 2000) in the Geosciences Lab at the University of Texas at Austin.

The ^{210}Pb activity was determined for both cores (BAR2 and D2, 10 and 25 samples respectively). Geochemical and grain size analyses were conducted for the BAR2, D2 and an additional core, named BAR1 (23 samples).

Approximately 1 g of dried sediment per sample was taken to conduct ^{210}Pb analysis and 1 ml of a ^{209}Po spike was added to each sample. The pre-prepared samples were brought to near dryness on a hot plate (90–100 °C) in the presence of 15.8 N HNO3 and posteriorly in 6 N HCl, with a ratio of 2 ml of acid per gram of sediment sample. The samples were rinsed with 0.5 M HCl into centrifuge tubes and centrifuged twice for 15 min (Aalto and Nittrouer, 2012). The resulting solutions were poured into beakers and ascorbic acid was added. Previously treated nickel discs were soaked in each solution for approximately 24 h, and the ionic polonium is deposited onto the discs. After 24 h, the discs are rinsed with deionized water and placed in an Ortec Octete Plus alpha spectrometer for 48 h to determine the activity of ^{210}Po granddaughter (which reaches secular equilibrium with ^{210}Pb). The geochronologies of the D2 and BAR2 cores were determined by applying the Constant Rate of Supply (CRS) model.

Particle size analyses for the 57 samples were conducted using a Fritsch Analyzette 22 Compact laser grain-sizer. For elemental composition, the 57 dried sediment samples were sieved through a 150-μm mesh, and analyzed by X-ray fluorescence with an Olympus BTX Profiler 384 XRF/XRD. Metals in sediments are a good indicator of pollution and, because of their resistance to decomposition in natural conditions, are among the most persistent pollutants in aquatic ecosystems (Arnason and Fletcher, 2003). Heavy metal concentrations of As, Zn, Cu, Ni, Mn, Fe, and Cr were identified and quantified. The sediment is considered contaminated if any of the sediment thresholds are exceeded (NYSDEC, 1999).

3. Results

3.1. Trends of fluvial fluxes into the coastal zone

Significant trends in annual water discharge and sediment load were identified by applying the M-K test for the Magdalena River at Calamar and the Canal del Dique at Santa Helena. All upward trends were significant at a 95% confidence level (Tables 1 and 2). The most downstream gauging station of the Magdalena River at Calamar represents the upstream processes of natural and human induced erosions. Thus, the Calamar series of fluvial fluxes can be used as an indicator of river input variability into the coastal zone and also as the main source of fluvial variability of the Canal del Dique. Water discharge and sediment load of the Magdalena River at Calamar showed significant upward trends during the whole period of record (Table 1). Furthermore, when looking at the post-2000 and 2005–2010 year periods, both series were characterized by steeper increases (Fig. 3A and B). For example, a mean water discharge of 7262 m^3/s during the 1940–2011 year period increased to 8833 m^3/s for the 2005–2011 year period, corresponding to an increase of 1677 m^3/s or 24% with respect to the inter-annual mean of the whole record (Table 2).

Fluvial fluxes from the Canal del Dique were also more pronounced after 2000 (Fig. 3). A mean water discharge of 398 m^3/s before 2000 increased to about 508 m^3/s during the 2000–2010 year period, corresponding to an increase of 28%. Also, sediment load displayed an increase of 48% when comparing the mean load of 16,153 t/day during the 1984–2000 year period with the observed inter-annual mean of 23,906 t/day for the 2005–2010 year period (Table 2). The magnitude of discharge change per unit time period, calculated as Sen's slope, also showed significant increases for both the Magdalena and Canal del Dique fluvial fluxes (Table 2).

The modified Mann-Kendall test for the Magdalena reveals significant upward trends in annual sediment load during the mid-1980s, 1990s, and post-2000 (Fig. 3C and D). The Canal del Dique water discharge shows significant upward and downward trends since 1985 (Fig. 3C). Meanwhile, sediment load exhibits a significant upward trend between 1991 and 2010. The interception point between the forward and backward components in 1991 indicates a trend inflection point over the significance level. This behavior continues until 2001 when sediment load experiences a slightly downward and more stable trend. In 2005, the sediment load increases until 2010 (Fig. 3D).

The mean annual sediment load transported by the Canal del Dique between 1984 and 2010 is 6.7 Mt/y. The total sediment flux delivered to Cartagena Bay during the same period is 1.9 Mt/y. During the 26 years of monitoring, the Canal del Dique has discharged approximately 177 Mt of sediment to Barbacoas and Cartagena Bays (Fig. 1). Meanwhile, the total sediment load discharged into Cartagena Bay during the same period is 52 Mt.

Comparing the historical inter-annual means of discharge and sediment load in the Magdalena River at Calamar with that of the Canal del Dique (Table 1), the Canal drains 5.9% and transports 4.5% of the Magdalena water discharge and sediment load, respectively. These proportions have increased in the post-2000 period with respect to the pre-2000 period (Table 2). Prior to the year 2000, the Canal del Dique received 5.4% and 4.1% of the Magdalena's water discharge and sediment load, respectively, whereas in the post-2000 period the proportions received by the Canal increased to 6.5% and 5.1%. This suggests that, over time, the Canal del Dique receives an increasing proportion of the Magdalena's water and sediment.

Table 1
Results of Mann-Kendall tests and Sen's slopes of the mean monthly water discharge and sediment load time series of the Magdalena River at Calamar and the Canal del Dique at Santa Helena.

	Mann-Kendall test						
Station-variable	First year	Last year	No. years	Tau-K	*p* Value	Interannual mean	Annual average Sen's slope
Calamar Q	1940	2011	71	0.101	$p < 0.0001$	7264	14.77 $m^3/s/y$
Calamar Q_s	1972	2011	39	0.150	$p < 0.0001$	400,684	3017 t/day/y
Dique Q	1979	2010	31	0.364	$p < 0.0001$	431	8.04 $m^3/s/y$
Dique Q_s	1984	2010	26	0.389	$p < 0.0001$	18,223	531 t/day/y

Note: Q = water discharge m^3/s; Q_s = sediment load t/day.

To estimate the periodicities and variability patterns and to distinguish temporal oscillations in water discharge of the Canal del Dique, the continuous wavelet transform was applied on monthly deseasonalized time series of water discharge (Fig. 3E). Water discharge series show an annual signal during the late 1980s and 1990s, and at the end of the 2005–2010 year period (Fig. 3E). These annual oscillations are significant at the 95% confidence level (Fig. 3F). The 6-month period appears highly intermittent, but it is more visible in 1983–1986 and 1994–1998 periods. Furthermore, the 2–4 year fluctuation appears in 1985–1995 and 1998–2005. Overall, the freshwater discharge of the Canal exhibits an intermittent quasi-decadal oscillation between 1989 and 2010.

3.2. Spatio-temporal variability of coastal waters suspended sediments

In general, water transparency has dramatically changed over 14 years at Rosario Islands National Park. Monthly averaged TSS maps throughout hydrological year between 2000 and 2015 show the spatio-temporal variability of the sediment plumes (Fig. 4) and indicate that coral reef waters in the region exceeded the threshold value set for the protection of open coastal reefs (i.e., 5–10 mg/l). The presence of turbid plumes was more pronounced throughout the May–July period and during the months of September and November (Fig. 4). These periods coincide with the observed seasonality of fluvial fluxes from the Magdalena River, which exhibits a bimodal behavior with medium discharges in the middle of each year and maximum fluxes during October and November. In addition, turbid plumes expulsed from the outlet of Cartagena Bay were observed between January and April, a period that coincides with the prevailing northeast trade winds in the region. In contrast, turbid waters from the Barbacoas Bays influenced the coral reef regions A3–A5 (Fig. 2) during the period between July and October, a season that corresponds to southwest trade winds. Finer sediments can travel further with the river plume movement and drive the sediment concentrations in the outer part of the river plume, as seen in coral reef regions A3 and A4 (Figs. 2 and 4). Overall, river plumes from the Magdalena River delta (Fig. 4, upper left) were interconnected with the plumes from the Cartagena and Barbacoas Bays and covered the whole inshore regions (Fig. 4).

To investigate annual TSS deviation patterns, we developed 14-years (2000–2013) TSS time series (Fig. 5), extracted from MODIS data (at every 8 days interval) at six virtual gauge windows (A1–6) indicated in Fig. 2. Overall, TSS concentrations throughout the analyzed period ranged up to 62.3 mg/l (Figs. 5 and 6). The regions A3 and A4 (Fig. 2) in the Rosario Islands exhibited TSS values of more than 3-standard deviations above the inter-annual mean during 2002–2003, 2007–2008, and 2009–2010 year periods. The spatial connection between the outlet of Cartagena Bay (A1 in Fig. 2) and Isla Grande (A4 in Fig. 2) can be observed through similar inter-annual fluctuations of extreme TSS deviations (Fig. 5).

Table 3 summarizes the annual deviations of TSS from the inter-annual mean and standard deviations for each MODIS time series window (A1–6) (Fig. 5). Annual percentages of time that each region experienced TSS values above the threshold limit (10 mg/l) (e.g., Fabricius, 2005; Erftemeijer et al., 2012) ranged from 100% in the outlet of the Canal del Dique (A6) to 17.4% in the distal reef region of Rosario Island (A4). Coral reef waters of Isla Grande (A3) were exposed to turbid waters between 19.6 and 47.8% of the whole analyzed time period. Nearly all the regions A1–A6 experienced a high degree of turbidity over the 2010–2011 wet season due to the strong La Nina beginning in mid-2010. For instance, major time exposures to high levels of TSS ($>\mu + 3\sigma$) in coral reef regions A3 and A4 occurred during La Nina events in 2003, 2008 and 2010–2011.

Box-whisker plots of time series TSS extracted from windows A1–6 (Fig. 2) show high interquartile ranges (Fig. 6). During the 2000–2013 year period mean TSS values ranged from 28.5 (A5) to 15.1 mg/l (A3). TSS values below 10 mg/l were rarely observed in the studied regions. In addition, all coastal regions with coral reef communities from the outlet of the Cartagena Bay (A1 in Fig. 2) to the distal region of the Rosario Island (A4 in Fig. 2) witnessed maximum values of TSS between 54.3 and 55.2 mg/l, almost twice the mean TSS of 28.5 mg/l observed at the outlet of the Canal del Dique (A6). Overall, TSS of the coral reef waters around the Rosario Islands National Park was rarely below 10 mg/l (Figs. 5 and 6).

3.3. Sedimentation rates and tracers of pollutants

Three cores were extracted in the coastal area of the Canal del Dique distributary channel (Fig. 1B) and analyzed to assess grain size and metal content. Two were studied to assess sedimentation rates for the lower Magdalena River: one in the Pasacaballos delta, an outlet of El

Table 2
Results of Mann-Kendall tests and Sen's slopes of the mean monthly water discharge and sediment load time series of the Magdalena River at Calamar and the Canal del Dique at Santa Helena for the three selected time periods, including Pre-2000, Post-2000, and 2005–2011.

Station-variable	Pre-2000					Post-2000				
	First year	Last year	Tau-K	Sen's slope	Interannual mean	First year	Last year	Tau-K	Annual average Sen's slope	Interannual mean
Calamar Q	1940	1999	0.082	13.53 $m^3/s/y$	7156	2000	2011	0.535	527.64 $m^3/s/y$	7783
Calamar Qs	1972	1999	0.163	4830 t/day/y	394,346	2000	2011	0.373	30,185 t/day/y	413,898
Dique Q	1979	1999	0.205	6.46 $m^3/s/y$	390	2000	2010	0.544	33.92 $m^3/s/y$	508
Dique Qs	1984	1999	0.414	912 t/day/y	16,153	2000	2010	0.436	1105 t/day/y	21,184
Calamar Q	–	–	–	–	–	2005	2011	0.222	599.50 $m^3/s/y$	8833
Calamar Qs	–	–	–	–	–	2005	2011	0.221	4779 t/day/y	495,794
Dique Qs	–	–	–	–	–	2005	2010	0.300	1491 t/day/y	23,906

Note: Q = water discharge m^3/s; Q_s = sediment load t/day.

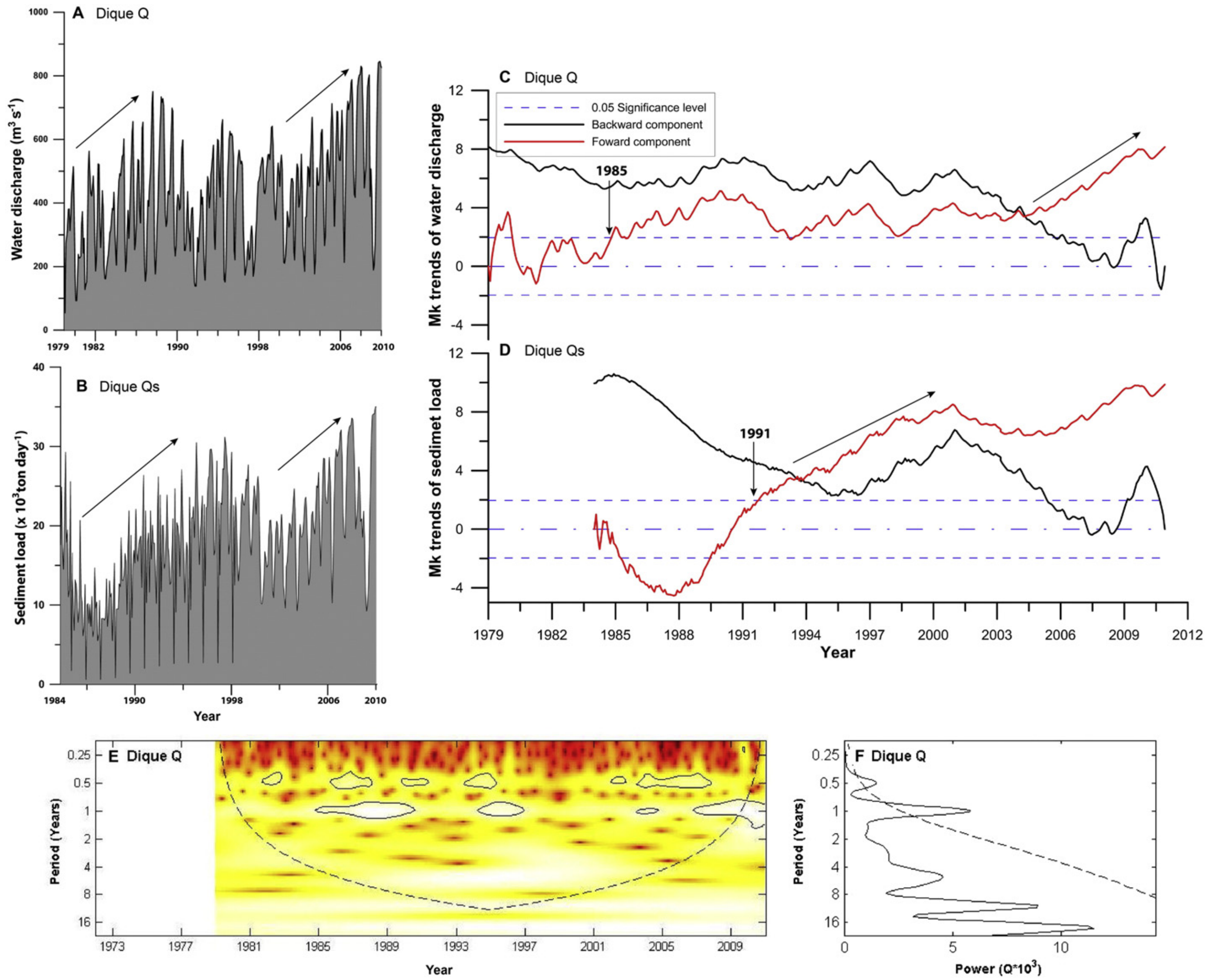

Fig. 3. (A–-B) Monthly series of fluvial fluxes for the Canal del Dique at Santa Helena (Fig. 1B). (C–D) Modified M-K trends of water discharge and sediment load for the Canal del Dique. Progressive and retrograde series are shown in red and black, respectively. (E) Continuous wavelet transform spectrum of water discharge for the Canal del Dique, showing high values of the transform coefficients (white) and the 95% confidence level (dashed blue line). (F) Global wavelet spectrum.

Dique into Cartagena Bay, and the other in the Barbacoas Bay, an area fed by a secondary delta system sourced by the Canal del Dique (Fig. 1B).

In all the cores, brown silt was the dominant grain size (81%) ranging from very fine silt (29.5%), fine silt (23.5%) and medium silt (18%). The proportion of coarse silt is ~11%, while clay averages about 19%. No sedimentary discontinuities or changes in grain size were observed in the cores, which are absolutely dominated by silty sedimentation. For that reason, the interpretation of the ^{210}Pb results was based on the Constant Rate of Supply (CRS) model. The ^{210}Pb activity is plotted against depth for both sediment cores (Fig. 7). The average accumulation rate for the core BAR2 at the Barbacoas Bay is 0.75 cm per year, and a similar value of 0.75 cm per year was estimated for core D2, in the Pasacaballos Delta.

Data in Table 4 synthesizes average values from (1) the Coastal Ocean Sediment Database (COSED) for marine and estuarine ecosystems; (2) Lowest Effect Level (LEL); and (3) Severe Effect Level (SEL) for the protection of aquatic organisms. When SEL is exceeded, the metal may severely impact biota health and the impact is considered moderate if only the Lowest Effect Level criterion is exceeded. In average, Zn, Cu, Ni, and Cr have greater concentrations than those of upper continental crust in both cores (Table 4 and Fig. 8). The average abundance (in ppm) of As, Zn, Cu, Ni, Cr, Mn and Fe (%) in D2 core were 7, 143, 50, 34, 9, 487, and 3.75%, respectively, and for the core BAR1 were 6, 157, 55, 48, 58, 373, and 4.22%, respectively. Core Bar2 is located at a more distal area from the Barbacoa Bay, a few kilometers away from the fluvial deltas. Even though the average values of concentration of heavy metals in Bar2 are lower than in Bar1 and D2, peaks of As, Cu, Ni, Mn, Fe can be above LEL, and Cr can even reach SEL values.

Concentrations in the proximal coastal zone exceed the lowest effect level and indicate moderate impact on aquatic organisms (Table 4 and Fig. 8). Abundances of As in the D2 and BAR1 sediments are relatively low, ranging from 0 to 13 ppm and 0–15 ppm, respectively. The abundance of Cr and Pb is very low for the two cores. Besides average values, the pulsating variability is noticeable in the concentration of metals which is in agreement with the variability of hydrosedimentological inputs of the Magdalena River to the coastal zone through the Canal del Dique (Figs. 7 and 8). The pulsatile input of clastic sediments imposed by the fluvial regime is even detected in the cores through the variability in the concentration of heavy metals. It is important to remark that very high values of Ni, Fe and Cr above the SEL standard are recorded in several samples. Cr is almost absent or negligible in the majority of the

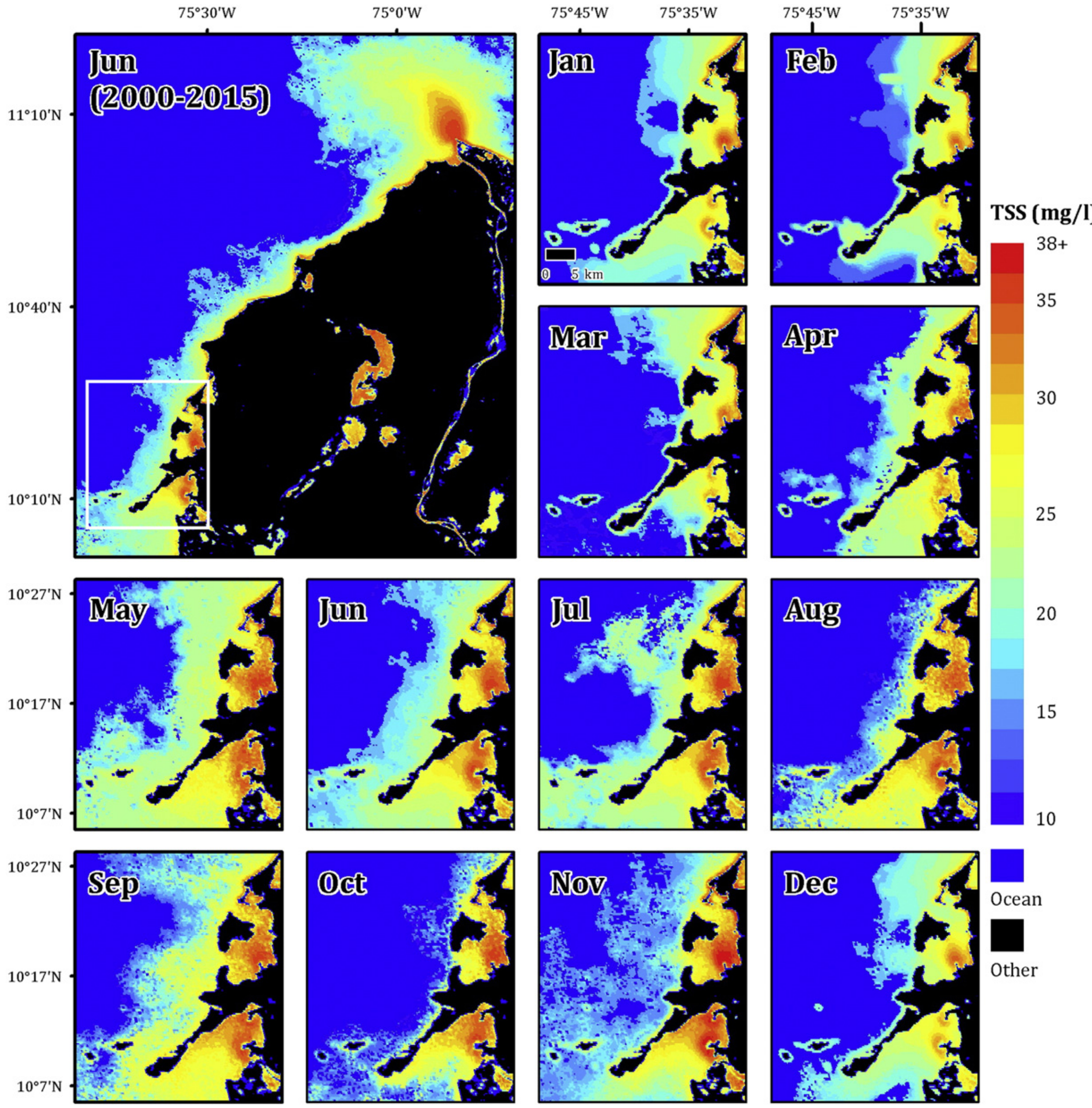

Fig. 4. 16-years (2000–2015) monthly averaged TSS maps throughout hydrological year showing the spatiotemporal variability of the sediment plumes. The upper-left image shows the entire extent of the sediment plume from June of these images, flowing southwestward from the mouth of the Magdalena River.

samples, but when recorded, its concentration is significantly high (SEL) (Fig. 8 and Table 4).

4. Discussion

4.1. Fluvial sediment fluxes into the coastal zone

There is a need for modeling the interactions between natural ecological processes and human impacts from the land runoff on coastal coral reefs. For example, a model proposed for the Great Barrier Reef, which explains coral and algae abundance on coastal reefs as a function of natural disturbances from tropical cyclones and turbid river floods, indicates that the rate of coral reef recovery depends on ambient water and substratum quality. The model suggests that increases in sediments from human activities will lead to reef degradation (Wolanski et al., 2004). In the coral reefs of the Rosario Islands, our results demonstrate that the presence of turbid plumes in the Rosario Islands is a constant stressor impacting reef water quality. For instance, coral waters in the main marine protected area of Colombia have rarely experienced non-turbid conditions during the last decade.

The transport and fate of fluvial sediments discharged into semi-open coastal systems close to near shore coral reefs vary considerably depending on the geological and oceanographic characteristics of the costal environment (Delandmeter et al., 2015). Many studies have proved that fluvial sediment inputs and the resuspension by wind, currents and tides of muddy sediments, affect the health and diversity of coral reefs, increasing the mortality and decline of the corals communities (e.g., Wolanski et al., 2005; Victor et al., 2006; Fabricius et al., 2013).

The impacts of fluvial muddy sediments on coral reefs have been thoroughly studied in small catchments of tropical islands and medium size fluvial basin from Australia such as the Burdekin River (Drainage basins = 129,700 km^2) (e.g., Wolanski et al., 2005; Golbuu et al., 2008; Storlazzi et al., 2009). With a mean annual sediment transport of 4 Mty^{-1}, the Burdekin is the main exporter of muddy sediment to the Great Barrrier (Delandmeter et al., 2015). However, annual and seasonal sediment fluxes in the Burdekin are highly variable because of the dry tropical hydro-climatic regime and the episodic short duration floods. In contrast, the hydro-sedimentological regime of the Magdalena-and the artificial Canal del Dique system provides a more extreme scenario on the sediment-corals relationships in the Caribbean

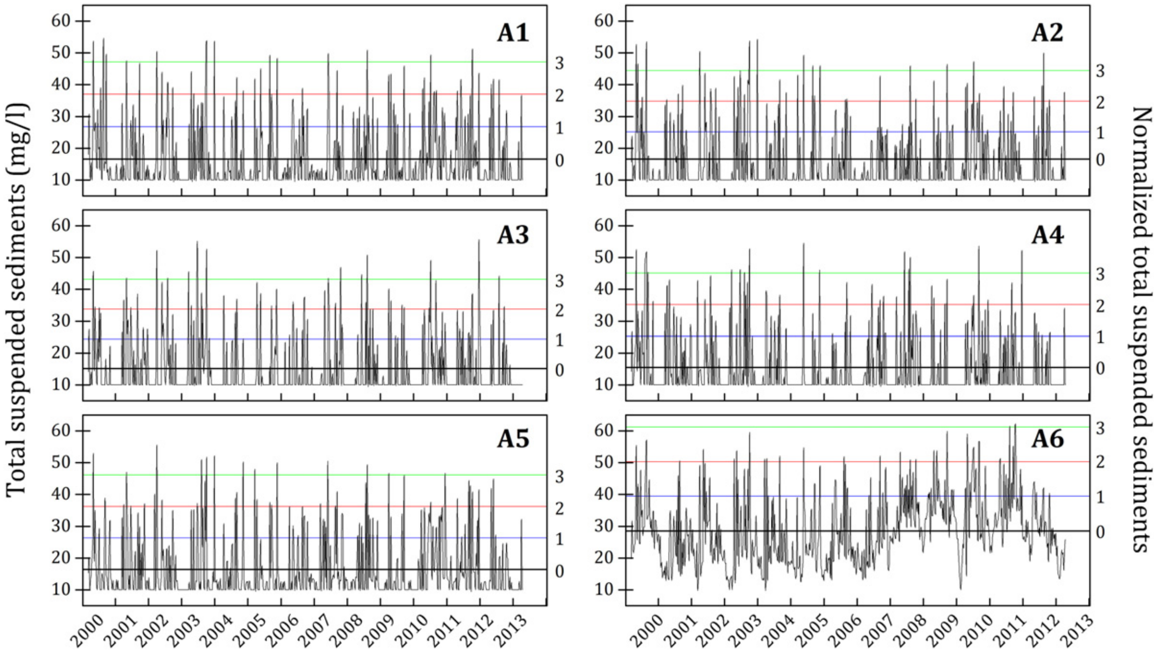

Fig. 5. Time series TSS (at every 8 days interval, 2000–2013) extracted from MODIS data at six virtual windows (A1–6) indicated in Fig. 2. These TSS series are standardized to assess their annual deviations from the inter-annual means (right-axis). Annual % TSS deviations are summarized in Table 3.

coast. The Canal del Dique sources ~8.7 MT/y of muddy sediments to the relatively small Cartagena and Barbacoas bays. While in some natural embayments the fluvial sediments are deposited near the river mouth and a smaller fraction is transported by a freshwater plumes, in our study area, the network of human-made channels transfer abruptly the sediments to the coastal system without a transitional natural buffer or environmental transition. After major hydraulic interventions in the Canal del Dique fifty years ago, which connected the Canal with the Barbacoas Bay (Fig. 1), the sudden input of fluvial sediments on the marine environments started and three major delta lobes were developed in the bay. At the distal zones of the prograding deltas, muddy sediments have been blanketing the shallow carbonate shelf (depth < 10 m) at an estimated accumulation rate of 0.75 cm per year. The semi-open character and the shallow waters of the Barbacoas and Cartagena bays suggest that during periods of low river discharge, strong oceanographic conditions may resuspend and transport bottom sediments in the near shore reefs, triggering additional negative effects on the coral communities. In addition, freshwater plumes transport muddy sediments through the deeper waters (>40 m) towards the more distal coral reefs of the Rosario Islands (Fig. 4).

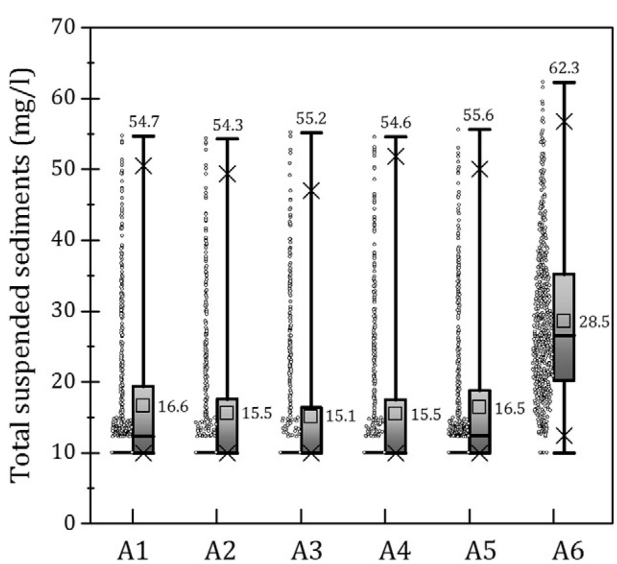

Fig. 6. Box-whisker plots of time series TSS extracted from windows A1–6 (locations in Fig. 2). Mean and maximum TSS values are indicated at the middle (next to squares) and top whisker, respectively. TSS data point distributions are shown next to the plots.

The exacerbation of the sediment inputs through time has been also detected. The downstream Magdalena and its distributary channel, the Canal del Dique, show significant trends in the water discharge and sediment load records. Between 2000 and 2011, trends in fluxes were more pronounced and annual discharges increased up to 48%. For example, the Magdalena streamflow and sediment load experienced increases of 24% and 33%, respectively, with respect to the pre-2000 period. Meanwhile, the Canal del Dique witnessed increases in water discharge and sediment load of 28% and 48%, respectively (Tables 1 and 2). These results are in close agreement with the observed trends during the period between 1980 and 2010 in sediment loads of the main tributaries of the Magdalena River and also with the steep increase in deforestation during the last three decades (Restrepo et al., 2015). In addition, our sedimentation rates in the outlets of the Canal del Dique also show major clastic fluvial sediment inputs (Fig. 7). The transference of sediments in the inner shelf of the Cartagena and Barbacoas Bays is also remarkable. While clastic sedimentation of mud in calcareous inner shelfs in natural conditions is almost undetectable, the human-induced input of muddy sediments to the bays through the Canal del Dique and secondary artificial channels is high, and sedimentation rates are of 0.7–0.8 cm y^{-1} in average in the coastal area (Fig. 7). In addition, heavy metals are being also transferred from the Magdalena. The detected values of As, Zn, Cu, Ni, Cr, Mn and Fe are above ecologically accepted standards (Fig. 8 and Table 4). Considering that the core sampled in Barbacoas Bay (Fig. 1) is upstream of the city of Cartagena, the record indicates that metals are being sourced through the Magdalena Basin upstream of the Canal del Dique at Calamar, and that Cartagena is not the only source of pollution in the bay.

Major sedimentation pulses (Fig. 7) coincide with the timing of major dredging and hydraulic interventions in the Canal, and also with the mentioned trends in sediment fluxes from upstream reaches of the basin. Thus, it is reasonable to expect that under the current trends of land-cover change in the Magdalena watershed, pulses of

Table 3
Summary of annual % TSS (mg/l) deviations from the inter-annual mean (μ) and standard deviations (σ) for each MODIS time series window (A1–6).

	2001					2002					2003				
	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T[a]	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T
A1	26.1	13.0	4.3	2.2	47.8	26.1	15.2	8.7	2.2	43.5	30.4	19.6	10.9	6.5	45.7
A2	28.3	17.4	6.5	0	37.0	26.1	17.4	8.7	2.2	34.8	30.4	21.7	17.4	4.3	41.3
A3	41.3	23.9	8.7	2.2	41.3	28.3	13.0	6.5	4.3	34.8	32.6	23.9	15.2	6.5	45.7
A4	37.0	17.4	4.3	0	45.7	28.3	10.9	6.5	0	39.1	28.3	19.6	13.0	8.7	41.3
A5	30.4	17.4	6.5	2.2	52.2	26.1	8.7	6.5	2.2	45.7	23.9	19.6	10.9	6.5	47.8
A6	19.6	4.3	2.2	0	100	32.6	10.9	2.2	0	97.8	26.1	15.2	6.5	0	95.7

	2004					2005					2006				
	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T
A1	15.2	10.9	4.3	0	37.0	26.1	13.0	8.7	4.3	47.8	30.4	17.4	2.2	0	60.9
A2	19.6	10.9	4.3	0	26.1	23.9	15.2	10.9	6.5	39.1	23.9	15.2	4.3	0	30.4
A3	19.6	8.7	4.3	0	19.6	23.9	13.0	8.7	0	28.3	21.7	17.4	4.3	0	26.1
A4	26.1	15.2	6.5	0	30.4	13.0	8.7	4.3	4.3	17.4	15.2	8.7	2.2	0	26.1
A5	23.9	8.7	6.5	2.2	47.8	23.9	13.0	8.7	4.3	47.8	19.6	15.2	2.2	0	56.5
A6	21.7	8.7	6.5	0	97.8	21.7	8.7	2.2	0	100	28.3	10.9	2.2	0	100.0

	2007					2008					2009				
	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T
A1	21.7	10.9	6.5	2.2	45.7	26.1	17.4	2.2	2.2	63.0	23.9	17.4	6.5	0	47.8
A2	28.3	8.7	2.2	0	34.8	28.3	10.9	4.3	2.2	34.8	23.9	13.0	4.3	2.2	30.4
A3	26.1	15.2	10.9	2.2	32.6	23.9	15.2	10.9	4.3	28.3	15.2	13.0	8.7	0	23.9
A4	30.4	15.2	6.5	0	39.1	30.4	19.6	8.7	6.5	39.1	13.0	10.9	8.7	0	17.4
A5	34.8	23.9	10.9	2.2	65.2	26.1	19.6	4.3	2.2	60.9	15.2	8.7	4.3	2.2	32.6
A6	26.1	10.9	2.2	0	100	76.1	21.7	6.5	0	100	91.3	30.4	6.5	0	100

	2010					2011					2012				
	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T	>μ	>μ + σ	>μ + 2σ	>μ + 3σ	>T
A1	50.0	26.1	10.9	2.2	67.4	34.8	19.6	8.7	2.2	69.6	23.9	13.0	6.5	0	39.1
A2	39.1	23.9	8.7	2.2	58.7	32.6	10.9	4.3	0	43.5	21.7	13.0	8.7	2.2	26.1
A3	43.5	23.9	6.5	2.2	47.8	32.6	21.7	4.3	2.2	34.8	17.4	8.7	4.3	2.2	19.6
A4	37.0	21.7	6.5	2.2	43.5	26.1	13.0	4.3	2.2	34.8	19.6	13.0	0	0	19.6
A5	50.0	32.6	4.3	2.2	71.7	32.6	17.4	10.9	0	69.6	21.7	6.5	4.3	0	45.7
A6	56.5	30.4	13.0	0	97.8	82.6	30.4	10.9	4.3	100	50.0	13.0	0	0	100

[a] T represents threshold of pristine reef condition, 10 mg/l.

turbid plumes from the Canal will continue as one of the main drivers of water quality degradation in the coral reefs of the Rosario Islands.

4.2. Are the sediment fluxes from the Magdalena linked to coral reef decline?

Human-induced changes in quality and quantity of terrestrial runoff have led to reef degradation by generating phase shifts, the processes by which areas formerly dominated by corals are overgrown by algae, without recovery (Wolanski et al., 2004). Thus, the cumulative effects of anthropogenic disturbances superimposed on natural disturbances make recovery less likely and, in some cases, result in stable states dominated by algae. According to Fabricius (2005), as nutrients increase, coral reef communities change from the dominance of nutrient-recycling symbiotic organisms such as corals to increasing proportions of macroalgae. The prevalence of macroalgae adds strong evidence to the conclusion that terrestrial runoff can limit or increase macroalgal biomass, and that they can have a negative effects on reef recovery (e.g. Birkeland, 1987).

In the wider scope of the Caribbean, average coral cover based on patterns of change from 1970 to 2012 is 14.3%. Live coral cover declined from 34.8% to 14.3% over the whole analyzed period. In contrast, macroalgal cover increased from 7% to 23.6% between 1984 and 1998. These opposite trends in coral and macroalgal cover constitute a large and persistent Caribbean phase shift from coral dominated to macroalgal dominated communities, which reached a peak by the mid-1990s and have persisted over 25 years since then (Jackson et al., 2014).

Initial interpretations of coastal ecosystems changes in relation to water discharge and sediment load from the Magdalena showed that increasing trends in sediment load coincided with the overall decline of live coral cover around the Rosario Islands (Restrepo et al., 2006b). A more recent study on community cover in the coral reef ecosystem of the Rosario Islands (Restrepo and Alvarado, 2011), based on an assessment from Alvarado-Chacón and Acosta (2009), indicates that the remaining live coral cover in the Rosario islands is 22%. Macroalgae cover (67%) is the dominant feature of the coral reefs at the Rosario Islands, and is three times higher than coral cover (Restrepo and Alvarado, 2011).

Study sites of reef development and community structure around the Rosario Islands were selected based on previous descriptions and data availability. These areas were at Barú, Grande, Rosario, and Tesoro Islands (Fig. 1). Community composition and coral and algal cover datasets were gathered from several studies made during the last two decades (i.e. Garzón-Ferreira and Kielman, 1995; INVEMAR, 2002; Lozano-Inderena, 1989; Navas et al., 2012; Ramírez et al., 1986; Restrepo and Correa, 2014; Sarmiento et al., 1990) and a survey carried out by the Institute of Marine and Coastal Research of Colombia, INVEMAR (Restrepo et al., 2006b). Comparisons between data sets collected as part of the ongoing INVEMAR survey and those collected prior to the 1990s enabled an assessment of changes that have taken place at four of the reef sites (Fig. 9).

Macroalgae cover (67%) is the dominant feature of the coral reefs at the Rosario Islands (Fig.9), about three times higher than the coral cover (22%) (Restrepo and Alvarado, 2011). The first report of coral reef composition in Rosario Islands (Pfaff, 1969) described healthy reef conditions of 48 species with vigorous growth rates. A decade later, coral

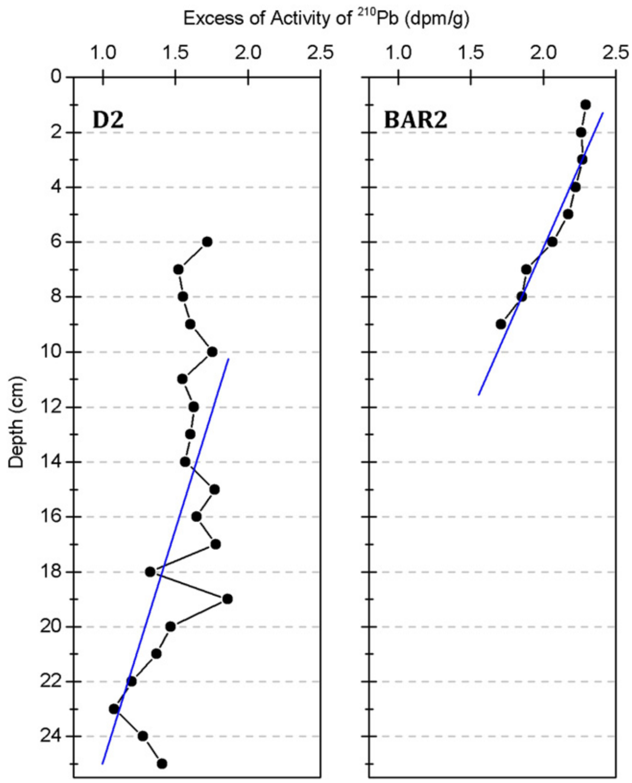

Fig. 7. ^{210}Pb sedimentation rates showing trends in the Pasacaballos delta at the Canal del Dique entrance in the Cartagena Bay and at the frontal zone of a secondary delta in the Barbacoas Bay (core locations in Fig. 1).

populations were in a good state of health (Werding and Sánchez, 1979), with live coral cover of 31% (Coral and Caycedo, 1983). *Acropora palmata* and *Acropora cervicornis* were the dominant corals representing 51% of total live coral cover at depths between 3 and 10 m. Other reported coral reef species included *Agaricia* spp. (9%), *Montastraea annularis* (7%), other coral species (13%), and the green algae *Halimeda opuntia* (8%) (Ramírez and de la Pava, 1981).

In the Rosario Islands, some studies between 1984 and 1989 saw the death of *A. palmata* to be 90% (e.g. Ramírez et al., 1986), loss of coral cover as well as increase in dead coral cover and in algae cover (Alvarado et al., 1986; Alvarado et al., 1992; Restrepo and Alvarado, 2011; Sarmiento et al., 1989) (Fig. 9). High sea surface temperatures, sedimentation and turbidity due to dredging activities in the nearby Canal del Dique, the use of dynamite, and an increase of uncontrolled tourism in the Rosario Islands were defined as the main causes of this environmental change (Restrepo and Alvarado, 2011).

A recent synthesis by Jackson et al. (2014) focuses on overfishing of parrotfish as a major cause of reef decline in the Caribbean. However, a recent workshop on *Caribbean coral reefs at risk*, held at the Teresa Lozano Long Institute of Latin American Studies, The University of Texas at Austin (September 2015), identified coastal development, elevated seawater temperatures, and land-based erosion associated with coral bleaching and diseases as the primary concerns in coral reefs of Mexico, Colombia, Puerto Rico and the US Virgin Islands. There is no need to identify a single stressor as the major problem throughout the Caribbean—in fact, it is misleading given the synergy and combination of a variety of different stressors affecting these ecosystems.

One of the major strategies for coastal reef management is to rely on marine protected areas. Managers draw a line around coral reefs on a map, inside of which extractive and destructive activities are prohibited or regulated. This management practice derives from limited ability to influence land management practices in adjacent drainage basins, based on the assumption that corals would recover from occasional human impacts from land runoffs. This management practice has proven insufficient where coral reefs are located near land and where human activities within adjacent river basins contribute to the decline of water and substratum quality (Wolanski et al., 2004). In fact, many studies have identified sediment and nutrient inputs as one of the major drivers of coral reef degradation (Fabricius, 2005; Restrepo et al., 2006b; Rogers, 1990; Wells, 1995).

The above situation is also observed in Colombia, where many difficulties are encountered in managing the impacts of fluvial fluxes on coral reef ecosystems (Restrepo and Alvarado, 2011). It has been shown here that the continental runoff from the Canal del Dique is discharged into the coral reefs of the Rosario Islands. Park authorities, local community, and the Ministries of the Environment and Transportation argue the lack of scientific studies proving the presence of turbid plumes in the region. Nevertheless, different institutional interests limit strategic alliances. Communication between scientists, managers, politicians, and industry is hardly met. For example, in the case of the major continental coral reef system in Colombia, the Rosario Islands, the results presented in this study sustain that fluxes from the Magdalena River and the Canal del Dique change the water quality standards in terms of turbidity levels expected in any healthy coral reef ecosystem (Restrepo and Alvarado, 2011; Restrepo et al., 2006b).

It is highly likely that most nearshore coral reef ecosystems are doomed to further decline under the predicted future climate change scenarios, which may result in prolonged sea surface warming trends, massive coral bleaching and diseases, and extreme weather events which may trigger increased runoff impacts to adjacent costal ecosystems (Ramos-Scharrón et al., 2015). Our results clearly demonstrate that water and sediment fluxes from the Magdalena River are one of the main stressors impacting the coral reefs in the Cartagena region and that the future research agendas must consider water quality monitoring systems and temporal mapping of the turbid plumes.

Table 4
Sediment quality criteria and metal concentrations (ppm) at cores.

Metals	UCC	COSED	LEL	SEL	D2 average	D2 max	BAR1 average	BAR1 max	BAR2 average	BAR2 max
As	1.5	13	6	33	7.36	13.40	4.93	14.74	0.79	8.72
Zn	71	135	120	270	143.01	171.70	153.34	178.31	94.59	105.50
Cu	25	42	16	110	50.03	77.64	56.02	85.79	13.52	37.67
Ni	20	42	16	50	33.57	77.24	48.44	75.25	6.90	42.12
Mn			460	1100	487.57	656.08	372.63	515.76	415.44	538.09
Iron %			2%	4%	3.75	4.20	4.11	4.54	3.16	3.48
Cr	35	125	26	110	8.74	114.40	41.49	132.65	22.75	128.23
Pb	20	45	31	110	0.92	23.03	0.59	13.03		

UCC = Upper continental crust.
COSED = Coastal ocean sediment database.
LEL = Lowest effect level.
SEL = Severe effect level.

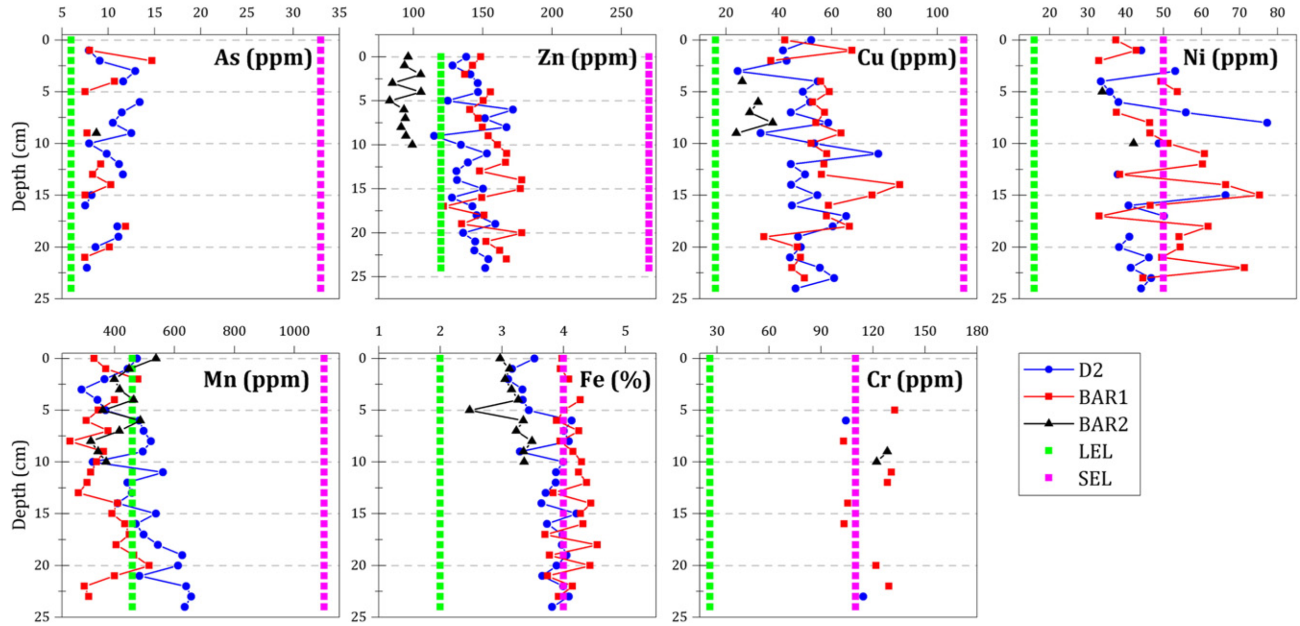

Fig. 8. Heavy metals in sediments (As, Zn, Cu, Ni, Mn, Fe, and Cr) are plotted in relation to depth. LEL (lowest effect level) and SEL (severe effect level) values are shown for reference as vertical bars.

5. Conclusions

This study, a framework to analyze the spatial and temporal variabilities of the muddy plumes of the Magdalena River and the Canal del Dique using MODIS satellite images, found that turbid river plumes have been more constant on coral reefs in the Cartagena region over the last decade. The Magdalena River plume TSS concentrations throughout the analyzed time witnessed maximum TSS values of 62.3 mg/l observed in coral reef waters of the Grande Island, more than twice the mean TSS of 28.5 mg/l measured at the outlet of the Canal del Dique. Recent average sedimentation rates of fluvial muddy sediments exported on the carbonate shelve are ~0.75 cm/y. An additional environmental stressor is the accumulation of heavy metals in the muddy sediments on the proximal deltas and those mantling the inner carbonate shelf.

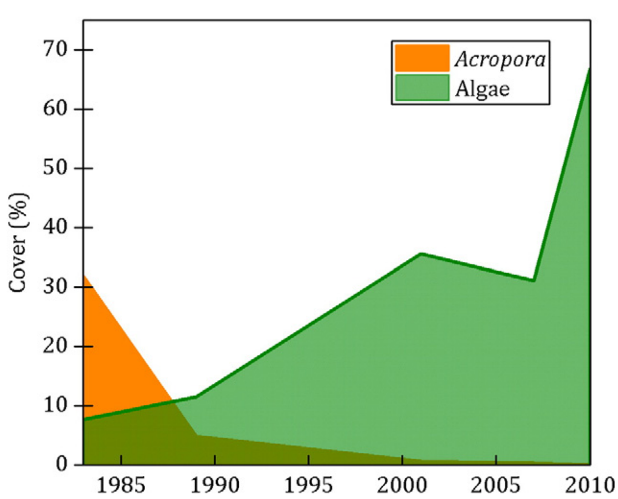

Fig. 9. Time series of *Acropora* and algae covers in the Rosario Islands National Park during the 1983–2010-period. Community composition and coral and algal cover datasets were gathered from several studies made during the last two decades (e.g. Ramírez et al., 1986; Sarmiento et al., 1990; Restrepo et al., 2006a,b) (data of coral and algae covers were grouped by Julio Andrade, Ecoral).

Sediment plume pulses were more pronounced during wet seasons of La Niña events in 2002–2003, 2007–2008, and 2009–2010. Reconstructed time series of MODIS TSS indicate that coral reef waters of Isla Grande were exposed to turbid waters between 19.6 and 47.8% of the entire analyzed 2000–2013-period. The TSS of the coral reef waters around the Rosario Islands National Park were rarely below 10 mg/l.

Estimating the balance between increasing and decreasing water discharge and sediment loads is of utmost importance for sound coastal zone and resource management. During the last decade, Magdalena streamflow and sediment load experienced increases of 24% and 33%, respectively, with respect to the pre-2000 year period. Meanwhile, the Canal del Dique witnessed increases in water discharge and sediment load of 28% and 48%, respectively. In general, the last decade has witnessed stronger increments in fluvial fluxes to the Cartagena coastal region, which clearly coincide with associated declines in water quality.

The multi-annual scale analysis presented here by reconstructing TSS time series seems to be a reliable tool for mapping water quality in coral reef regions exposed to high levels of river fluxes in the Caribbean. The frequency of occurrence of these turbid water types is relevant to understand the spatial and temporal scales of the land-based risks that affect coral ecosystems and help to define the geographical and temporal scales over which ecological impacts should be monitored and mitigated.

Our results emphasize the importance of local stressors, such as runoff and dispersion of turbid plumes, as opposed to ocean warming, disease and hurricanes, which have played a larger role on other coral reefs in the Caribbean. Coral reef management across the southwestern Caribbean, a coastal region influenced by continental fluxes of numerous rivers flowing from the Andes, may only be effective when land and marine-based stressors are simultaneously mitigated.

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