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Fluvial fluxes from the Magdalena River into Cartagena Bay, Caribbean Colombia: Trends, future scenarios, and connections with upstream human impacts

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ABSTRACT

Fluxes of continental runoff and sediments as well as downstream deposition of eroded soils have severely altered the structure and function of fluvial and deltaic-estuarine ecosystems. The Magdalena River, the main contributor of continental fluxes into the Caribbean Sea, delivers important amounts of water and sediments into Cartagena Bay, a major estuarine system in northern Colombia. Until now, trends in fluvial fluxes into the bay, as well as the relationship between these tendencies in fluvial inputs and associated upstream changes in the Magdalena catchment, have not been studied. Here we explore the interannual trends of water discharge and sediment load flowing from the Magdalena River-Canal del Dique system into Cartagena Bay during the last three decades, forecast future scenarios of fluxes into the bay, and discuss possible connections between observed trends in fluvial inputs and trends in human intervention in the Magdalena River basin. Significant upward trends in annual runoff and sediment load during the mid-1980s, 1990s, and post-2000 are observed in the Magdalena and in the Canal del Dique flowing into Cartagena Bay. During the last decade, Magdalena streamflow and sediment load experienced increases of 24% and 33%, respectively, compared to the pre-2000 year period. Meanwhile, the Canal del Dique witnessed increases in water discharge and sediment load of 28% and 48%, respectively. During 26 y of monitoring, the Canal del Dique has discharged ~177 Mt of sediment to the coastal zone, of which 52 Mt was discharged into Cartagena Bay. Currently, the Canal drains 6.5% and transports 5.1% of the Magdalena water discharge and sediment load. By 2020, water discharge and sediment flux from the Canal del Dique flowing to the coastal zone will witness increments of ~164% and 260%, respectively. Consequently, sediment fluxes into Cartagena Bay will witness increments as high as 8.2 Mt y^{-1} or 317%. Further analyses of upstream sediment load series for 21 tributary systems of the main Magdalena during the 2005–2010 period reveal that six tributaries, representing 55% of the analyzed Magdalena basin area, have witnessed increasing trends in sediment load, raising the river's sediment load by 44 Mt y^{-1}. Overall, trends in sediment load of the Magdalena and the Canal del Dique during the last three decades are in close agreement with the observed trends in human induced upstream erosion. The last decade has witnessed even stronger increments in fluvial fluxes to Cartagena Bay. Our results emphasize the importance of the catchment-coast linkage in order to predict future changes of fluvial fluxes into Caribbean estuarine systems.

1. Introduction

The Magdalena River (Fig. 1), one of the world's top 10 rivers in terms of sediment fluxes to the ocean (184 Mt y^{-1}; Restrepo et al., 2015), contributes ~9% of the total sediment load discharged from the eastern basins of South America (Restrepo and Kjerfve, 2000a). In addition, the Magdalena River, with a sediment yield of 710 t km^{-2} y^{-1} (Restrepo et al., 2015), appears to have the highest sediment yield of the large rivers along the Caribbean and Atlantic coasts. It is almost three times greater than the yield of the Amazon, 167 t km^{-2} y^{-1}; Orinoco, 158 t km^{-2} y^{-1}; and much greater than the yield of the Parana, 43 t km^{-2} y^{-1}; Uruguay, 16 t km^{-2} y^{-1} (Latrubesse et al., 2005); and São Francisco, 10 t km^{-2} y^{-1} (Milliman and Farnsworth, 2011).

The water and sediment discharges of the Magdalena River have great environmental and economic impacts on the adjacent coastal ecosystems. The Magdalena River fluxes used to flow into the southwestern Caribbean through its natural delta in Barranquilla until the late 1920s, when the Colombian government started major hydraulic works and dredging operations in the Canal del Dique, a 114-km-long man-made channel from the Magdalena River at Calamar to the bays of Cartagena and Barbacoas (Fig. 1). The enlargement works along this artificial channel took place during the 1923–1930, 1951–1952, and 1981–1984 periods to accommodate larger river vessels in the Canal. Since the

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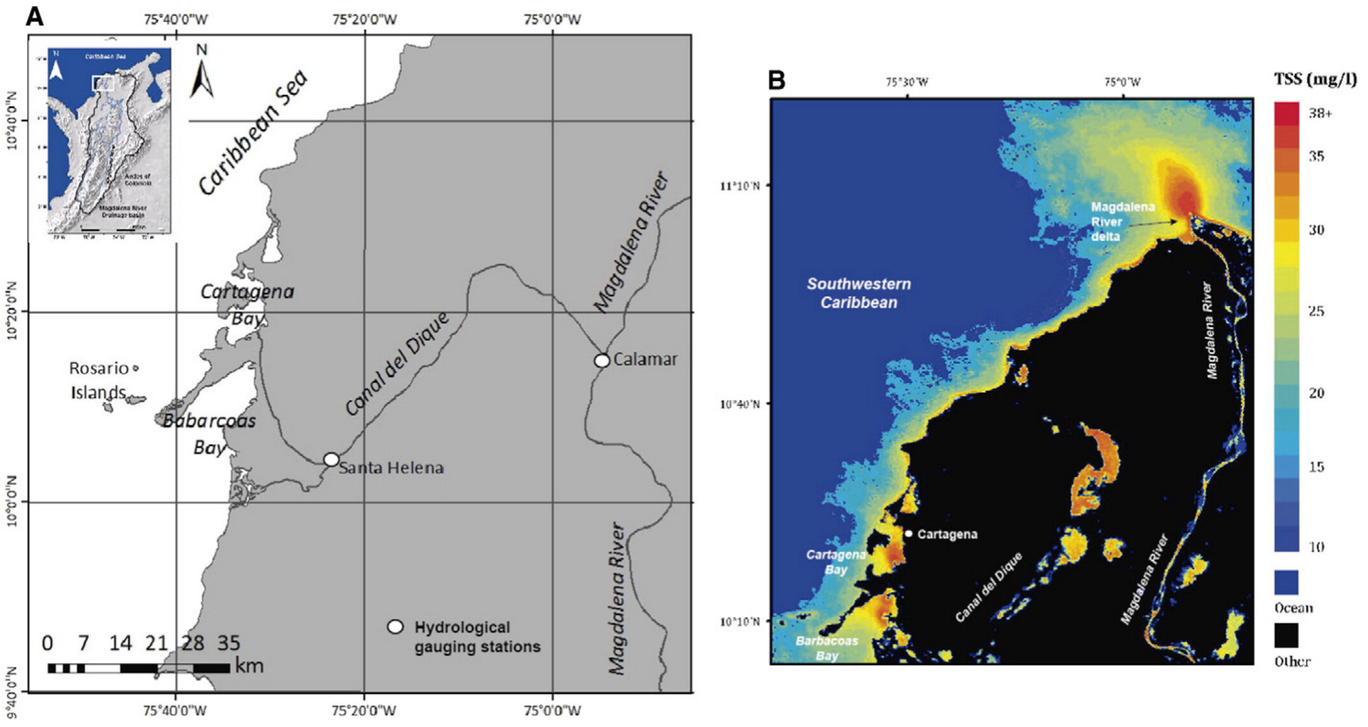

Fig. 1. (A) Location of the Magdalena drainage basin in the northern Andes, showing the lower course of the Magdalena River and its distributary channel, the Canal del Dique, and the hydrological gauging stations at Calamar and Santa Helena. (B) In situ calibrated MODIS satellite image to capture the spatiotemporal variability of the distribution of suspended sediment over the northern Caribbean of Colombia, showing the muddy plumes (red) of the Magdalena River in its delta mouth and the Canal del Dique in the bays of Barbacoas and Cartagena. This image is based on MODIS daily (MOD/MYD09GQ, L2) and an 8-day composite (MOD/MYD09Q1, L3) data from Terra and Aqua satellites at 250-m spatial resolution. Mapping of surface sediment plumes and values of total suspended sediments (TSS) concentrations are based on a calibration model to predict surface sediment concentration as a function of surface reflectance (band 1; Restrepo et al., 2016; courtesy of Edward Park).

major Canal channeling in 1952, the Magdalena fluxes have flowed directly into the bays of Barbacoas and Cartagena (Mogollón, 2013). Ecological analyses have shown that of nearly 850 ha of seagrass existing in Cartagena Bay in the 1930s, only 76 ha remained in 2001, which is <8% of the original cover (Restrepo and Syvitski, 2006). Also, live corals present in Cartagena Bay during the 1950s nowadays lie buried by sediments from the Canal del Dique (Mogollón, 2013).

A more recent study that analyzes 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 coastal ecosystems in the Cartagena region over the last decade. Large sedimentary plumes are developed and the amount of sediments delivered to the coastal sea is huge (Restrepo et al., 2006). As an example, the sediment load discharged in the Cartagena region is much larger than that delivered by the Burdekin River in Australia, which is threatening the Great Barrier Reef (Delandmeter et al., 2015). Another additional environmental stressor is the accumulation of heavy metals in the muddy sediments on the proximal deltas and those mantling the inner carbonate shelf. In addition, stronger increments in fluvial fluxes to the Cartagena coastal region clearly coincide with associated declines in water quality (Restrepo et al., 2016).

Previous studies have explored the magnitude and variability of water discharge and sediment load from the Magdalena River into the Caribbean (Restrepo and Kjerfve, 2000a; Restrepo, 2008; Restrepo et al., 2006, 2014). However, a detailed study of sediment fluxes from the Canal del Dique has not previously been conducted. Our objective is to study the magnitude and temporal trends of sediment load flowing from the Canal del Dique into Cartagena Bay during the last three decades. We present short-term future scenarios of water discharge and sediment load into the bay and discuss possible connections between observed trends in fluvial inputs and trends in human intervention in the Magdalena River basin.

The coastal region of Cartagena faces many environmental challenges, including development plans such as waterways, ports, and industry along with touristic expansions. However, impacts to coastal water quality have the potential to disrupt the local economies of tourism and artisanal fisheries and to degrade the ecosystem of the adjacent marine-protected area of the Rosario and San Bernardo Islands. On the other hand, sediment fluxes to the coastal zone are increasing because of the poor environmental management of the Magdalena River basin and the lack of perception by the environmental authorities on how the fluvial system works and the interactions of the river-coast. The cascade-interlinked effect on a fluvial basin and coastal system is not taken into account in policy-making and environmental conservation. Meanwhile, deforestation in remote parts of the Andes produces impacts in the floodplains of the river or even in the coastal-marine zone. The data and analyses presented here emphasize that coastal management in the Cartagena region may only be effective when land and marine-based stressors are simultaneously mitigated. Also, our results consist of first-hand information for decision makers who, until now, have lacked a reliable analysis of fluvial fluxes into the bay during the last three decades.

2. Materials and methods

2.1. Study area

The Magdalena River is the largest river system of the northern Andes of Colombia (Fig. 1), with a length of 1612 km. The drainage basin area covers 257,438 km^2, 24% of Colombia, and occupies a considerable portion of the Colombian Andes. With its headwaters located at an elevation of 3685 m, the river drains active orogenic mountain belts characterized by high relief as well as intense seismic and volcanic activity. The geomorphic setting of the Magdalena comprises subsiding foreland areas and an anastomosing river pattern (Latrubesse et al., 2005).

The mean annual water discharge of the Magdalena River is 7200 m^3 s^{-1} with an annual volume of water discharged into the Caribbean Sea of 228 km^3 (Restrepo et al., 2006a). Sediment load along the Magdalena River during the period 1980–2000 shows an increasing trend downstream, from 51 Mt y^{-1} at the upper course to 144 Mt y^{-1} in the lower reach. About 35% of the annual sediment load in the lower Magdalena drainage basin is derived from the upper basin. The mean specific sediment yield for the whole Magdalena basin is 689 ± 528 t km^{-2} y^{-1} (Restrepo and Syvitski, 2006). During the 1972–2000 period, the Magdalena River has delivered ~4022 Mt of sediment to the Caribbean coast. The 28-year mean sediment load is 144 Mt y^{-1}. This interannual mean of sediment load is equal to 86% of the total sediment load of all Colombian rivers draining into the Caribbean (Restrepo, 2008).

Fluxes of the Magdalena River are partially diverted to the bays of Barbacoas and Cartagena through the Canal del Dique distributary channel (Fig. 1). Since the 1920s, the government of Colombia has dredged and rectified the Canal del Dique. Major dredging and enlargement operations took place during the 1923–1930, 1951–1952, 1981–1984, and 1992–1994 periods. Since the canal's major channeling in1952, the Magdalena fluxes have reached and impacted the bays of Barbacoas and Cartagena (Mogollón, 2013), as well as the coral reef complex of the Rosario Islands (Restrepo et al., 2016; Fig. 1).

Cartagena Bay is an estuary with an approximate area of 84 km^2 and is connected to the Caribbean Sea by two straits: Bocagrande and Bocachica. Mean and maximum depths are 16 and 33 m, respectively (Molares, 2004). Two main superficial sediments types are in Cartagena Bay: (i) sediments of high-energy, shallow marine environments with high fluvial influence, and (ii) turbidity current deposits with high fluvial influence. Sediments with the lowest sand content (<5%) are located along a latitudinal axis running from the Canal del Dique prodelta. Autogenous calcareous sediments are covered by fine terrigenous sediment transported through the canal, which has a more active and dominant role in the bay's sediment deposition than previously reported (Restrepo et al., 2013). For instance, sediment fluxes into the bay during the 1961–2009 period have caused sedimentation and growth of the Canal del Dique delta, with a prograding rate of 4.17 m y^{-1}. The total sediment volume deposited into Cartagena Bay during the 1996–2004 period is 23.9 Mt (Marriaga and Echeverry, 2011).

Water exchange in Cartagena Bay is governed by tidal movement through its two seaward straits and the influent discharge of freshwater and suspended sediments from the Canal del Dique. The area is characterized as microtidal, with tidal range varying between 20 and 54 cm (Molares and Mestres, 2012). Freshwater discharge from the Canal del Dique produces estuarine conditions in the bay characterized by a surface layer of low salinity and high turbidity. The Canal del Dique drains ~6.5% of the Magdalena River's waters, and so estuarine conditions in Cartagena Bay are strongly related to the seasonal variation of runoff from the Magdalena River watershed (Restrepo, 2008).

2.2. Water discharge and sediment load data

In this study, data of water discharge (1940–2011) and suspended sediment load (1972–2011) in the Magdalena River from the downstream station at Calamar, which is located 112-km upstream of the Caribbean (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 discharge (1979–2010) and sediment load (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 ADCP daily stage readings, while sediment load estimates are derived from point samples of sediment concentrations measured at each outlet cross section by IDEAM-Uninorte, cross-multiplied with water discharge (Alvarado, 2008). To assess the percentage of sediment load discharged into Cartagena Bay, we analyzed data on sediment concentrations and loads measured at each of the Canal del Dique's outlets flowing into the bays of Barbacoas and Cartagena (Fig. 1; Corredor and Castro, 2008).

2.3. Trends and patterns of fluvial flux variability

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 the Canal del Dique at Santa Helena (Fig. 1). The Sen's slope, a nonparametric procedure for estimating the slope of trend in the sample of any N pair data, was used to test for 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 (Mann, 1945; Kendall, 1955; Kendall and Stuart, 1967). 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 ($k = 1, 2 \dots$ 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, an 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., Morlet wavelet spectrum) that were stretched and translated to both a frequency and time resolution (Torrence and Campo, 1998; Restrepo et al., 2014). This robust technique supports the evaluation of time series containing nonstationarities 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).

To explore relationships between hydrological anomalies and the El Niño Southern Oscillation-ENSO cycle, a low-pass frequency Butterworth filter is applied to remove high frequency oscillations and emphasize the interannual variability of fluvial fluxes. The filter is of the eighth order with a half-gain frequency of 0.045 cycles per month. This method is applied by performing a zero-phase digital filtering, processing the input data in the forward and reverse directions, and yielding zero-phase distortion (Shumway and Stoffer, 2004). In order to assess how much variability of water and sediment fluxes is explained by the ENSO cycle, filtered time series of water discharge and sediment load of the Magdalena and Canal del Dique are correlated via regression analysis with filtered series of the Southern Oscillation Index, SOI (defined as the sea level pressure difference between Tahiti and Darwin; Glantz, 1997).

2.4. Predictions of fluvial fluxes into Cartagena Bay

To make predictions of water discharge and sediment flux into Cartagena Bay, an *ARIMA-ARCH* model is applied and tested. The time period of 2000–2010 is selected for stochastic modeling. Because of the strong seasonality shown by the water discharge and sediment load series in the autocorrelation and partial autocorrelation analyses, we

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.

Station-variable	Mann-Kendall test 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 $m^3 s^{-1}$/y
Calamar Q_s	1972	2011	39	0.150	$p < 0.0001$	400,684	3017 t/d/y
Dique Q	1979	2010	31	0.364	$p < 0.0001$	431	8.04 $m^3 s^{-1}$/y
Dique Q_s	1984	2010	26	0.389	$p < 0.0001$	18,223	531 t/d/y

Note: Q = water discharge $m^3 s^{-1}$; Q_s = sediment load t/d.

simulate the stochastic component of the time series with a seasonal autoregressive integrated moving average model (SARIMA; Box and Jenkins, 1970). This SARIMA model has an order of $(p,d,q) \times (P,D,Q,s)$ and is expressed by the following the equation:

$$\phi_p(L)\Phi_p(L^s)\Delta^d\Delta^D y_t = \theta^q(L)\Theta_Q(L^s)\varepsilon_t \tag{1}$$

where $\phi_p(L)$ and $\theta^q(L)$ are the lag polynomials of the ordinary ARIMA (p,q) structure and Δ^d is the ordinary differentiation of the series. Therefore, $\Phi_p(L^s)$ and $\Theta_Q(L^s)$ are the lag polynomials of the seasonal ARIMA (P,Q) structure, Δ^D is the seasonal differentiation of the series, and s is the seasonal order, which is equal to 12 in a monthly series. Finally, ε_t denotes a sequence of random variables with zero mean and unit variance. Later, we perform a Lagrange multiplier (LM) test for detecting autoregressive conditional heteroskedasticity (ARCH) or high volatility in water discharge and sediment load series. The ARCH test consists of the following steps: (i) estimation of ordinary least squares (OLS), (ii) calculation of the determination coefficient (R^2) of the regression between observed and simulated series of sediment load, and (iii) hypothesis testing for the LM test, which is defined as:

$$H_0 = \alpha_1 = \alpha_2 = \cdots = \alpha_p = 0 \tag{2}$$

$$H_\alpha = \exists_j | \alpha_j \neq 0 \tag{3}$$

The null hypothesis is rejected if the experimental statistic is greater than the theoretical statistic or if the p-value is less than a significance level α.

Using the SARIMA model, two kinds of forecasts are performed. The stochastic forecast, also called one-step ahead forecast, is used for simulating a series of fluvial fluxes during the 2011–2012 period, while the dynamic forecast of trends (DFT), also called n-step ahead, is applied to detect trends in water discharge and sediment load during the 2011–2020 period. To obtain a smooth estimate of the long-term trend component of the time series, the DFT is combined with a Hodrick-Prescott filter (HP) (Hodrick and Prescott, 1980). To determine extreme values in the time series, the Log-normal probability distribution function (PDF) is applied (Chow et al., 1994). The PDF method allows defining different scenarios of water and sediment discharges, including return periods (T) of 2.33 and 10 y.

2.5. Connections with upstream trends in erosion and human impacts

To make further comparisons between sediment load trends and human activities that promote sediment production in the Magdalena River basin, including deforestation, agriculture, mining, urbanization, and energy, we analyzed data of global (FAO, 2010; Ferretti-Gallon and Busch, 2014), humid tropics (Geist and Lambin, 2001, 2002; Kim et al., 2015), and Colombian (Etter and van Wyngaarden, 2000; Armenteras and Rodríguez, 2005; Etter et al., 2005; 2006a, b, c, 2008; IDEAM, 2011, 2014; Restrepo et al., 2015) deforestation assessments. Further regional studies of erosion trends and economic indicators of human activities in the Andes mountains of Colombia (Restrepo, 2005; Restrepo and Syvitski, 2006; Restrepo, 2013; Restrepo et al., 2015) were also consulted.

3. Results

3.1. Trends in fluvial fluxes from the Magdalena-Canal del Dique system

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 record (Table 1). Furthermore, when looking at the post-2000 and 2005–2010 periods, both series were characterized by steeper increases (Fig. 2). For example, a mean water discharge of 7262 $m^3 s^{-1}$ during the 1940–2011 period increased to 8833 $m^3 s^{-1}$ for the 2005–2011 period, corresponding to an increase of 1677 $m^3 s^{-1}$ or 24% with respect to the interannual mean of the whole record (Table 2).

Fluvial fluxes from the Canal del Dique at Santa Helena (Fig. 1) were also more pronounced after 2000 (Fig. 2). A mean water discharge of 398 $m^3 s^{-1}$ before 2000 increased to about 508 $m^3 s^{-1}$ during the

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.

	Pre-2000					Post-2000				
Station-variable	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 7783	1940	1999	0.082		13.53 $m^3 s^{-1}$/y	7156	2000	2011	0.535	527.64 $m^3 s^{-1}$/y
Calamar Qs	1972	1999	0.163	4830 t/d/y	394,346	2000	2011	0.373	30,185 t/d/y	413,898
Dique Q	1979	1999	0.205	6.46 $m^3 s^{-1}$/y	390	2000	2010	0.544	33.92 $m^3 s^{-1}$/y	508
Dique Qs	1984	1999	0.414	912 t/d/y	16,153	2000	2010	0.436	1105 t/d/y	21,184
Calamar Q	–	–	–	–	–	2005	2011	0.222	599.50 $m^3 s^{-1}$/y	8833
Calamar Qs	–	–	–	–	–	2005	2011	0.221	4779 t/d/y	495,794
Dique Qs	–	–	–	–	–	2005	2010	0.300	1491 t/d/y	23,906

Note: Q = water discharge $m^3 s^{-1}$; Q_s = sediment load t/d.

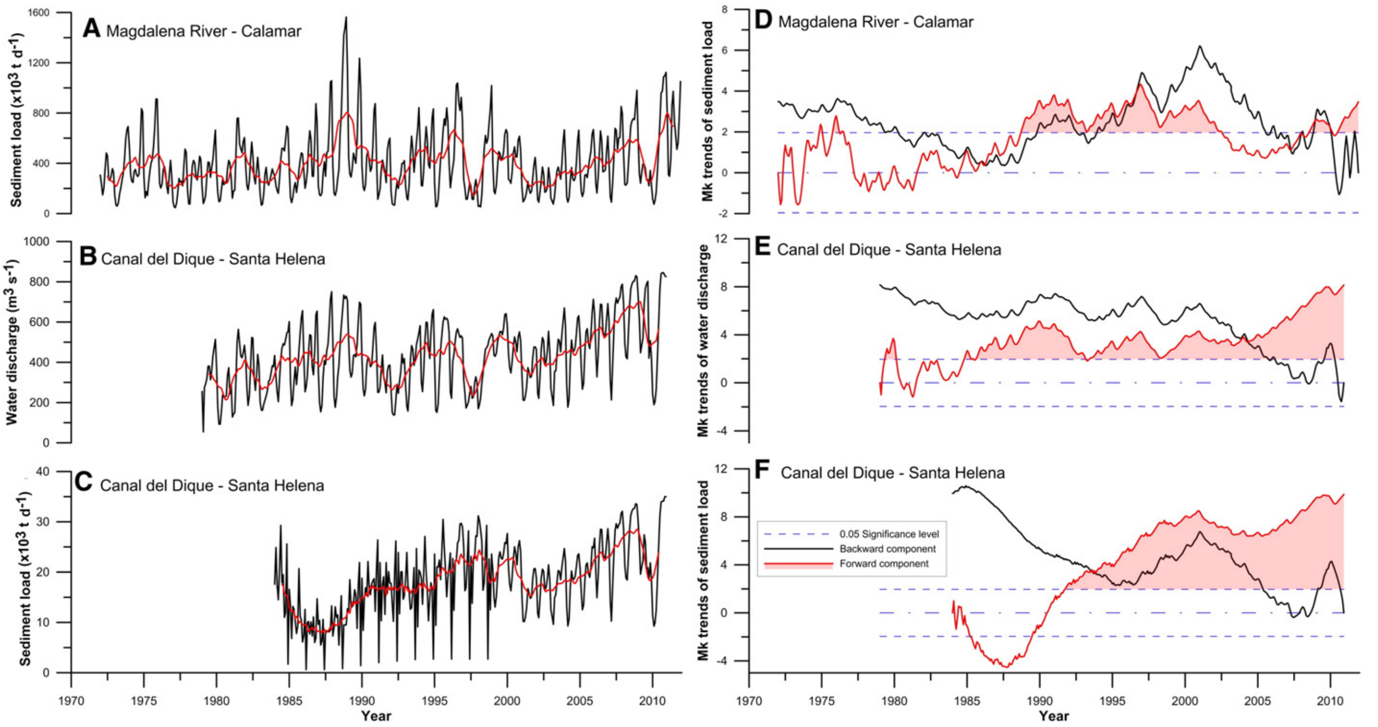

Fig. 2. (A–C) Monthly (black) and two-year running mean (red lines) series of fluvial fluxes for the Magdalena River at Calamar and the Canal del Dique at Santa Helena (Fig. 1). (D–F) The modified Mann-Kendall trends of water discharge and sediment load for the Magdalena River at Calamar and the Canal del Dique at Santa Helena. Progressive and retrograde series are shown in red and black, respectively.

2000–2010 period, corresponding to an increase of 28%. Also, sediment load displayed an increase of 48% when comparing the mean load of 16,153 t d^{-1} during the 1984–2000 period with the observed interannual mean of 23,906 t d^{-1} for the 2005–2010 period (Table 2). The magnitude of discharge change per unit time period, calculated as Sen's slope, also showed significant increases for 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. 2). The Canal del Dique water discharge shows significant upward and downward trends since 1985 (Fig. 2). 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. 2).

The mean annual sediment load transported by the Canal del Dique at Santa Helena between 1984 and 2010 is 6.7 Mt y^{-1}. The total sediment flux delivered to Cartagena Bay during the same period is 1.9 Mt y^{-1}. During the 26 y of monitoring, the Canal del Dique has discharged ~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 interannual 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%, respectively. This suggests that, over time, the Canal del Dique receives an increasing proportion of the Magdalena's water and sediment.

3.2. Interannual variability, connections with El Niño (ENSO) and temporal oscillations

Previous analysis of sediment load deviations for the 1984–2000 period shows that the Canal del Dique experienced 7 y, or 50%, of the total sediment load variability, in which the annual sediment load exceeded 50% of the mean (Restrepo et al., 2006a). The analysis presented here, which covers a longer period (1984–2010), indicates that the post-2000 period is characterized by positive deviations, as seen in the anomalies of sediment load above or below the interannual average (Fig. 3). Clearly, positive deviations during the 1998–2000, 2008–2009, and 2010–2011 periods coincide with La Niña anomalies (Fig. 3).

Regression analysis between the smoothed (12-month running mean) SOI and the smoothed Canal del Dique water discharge of 1979–2010 yielded a coefficient of variation of $R^2 = 0.37$ (Fig. 3), significant at the 95% confidence level, which indicates that variations in the SOI explain 37% of the variability in discharge, with high values of the SOI corresponding to peak La Niña conditions and peak canal discharge (Fig. 3). In contrast, regression between SOI and Canal del Dique sediment load does not reveal any significant relationship (Fig. 3), suggesting that sediment fluxes into Cartagena Bay are not controlled by the phases of the ENSO. Other physical and human-induced processes may control the flux of sediments from the canal into the bay, including sediment transfer from flood plains and associated wetlands during falling limbs in the canal and dredging operations along the main channel. For instance, the connections between the Canal del Dique and its associated floodplains have been altered by major dredging and channeling works since 1952. Now the Canal functions as a straight channel with low sediment retention on marginal floodplains. According to a grain size analysis carried out on the Canal del Dique, no sedimentary

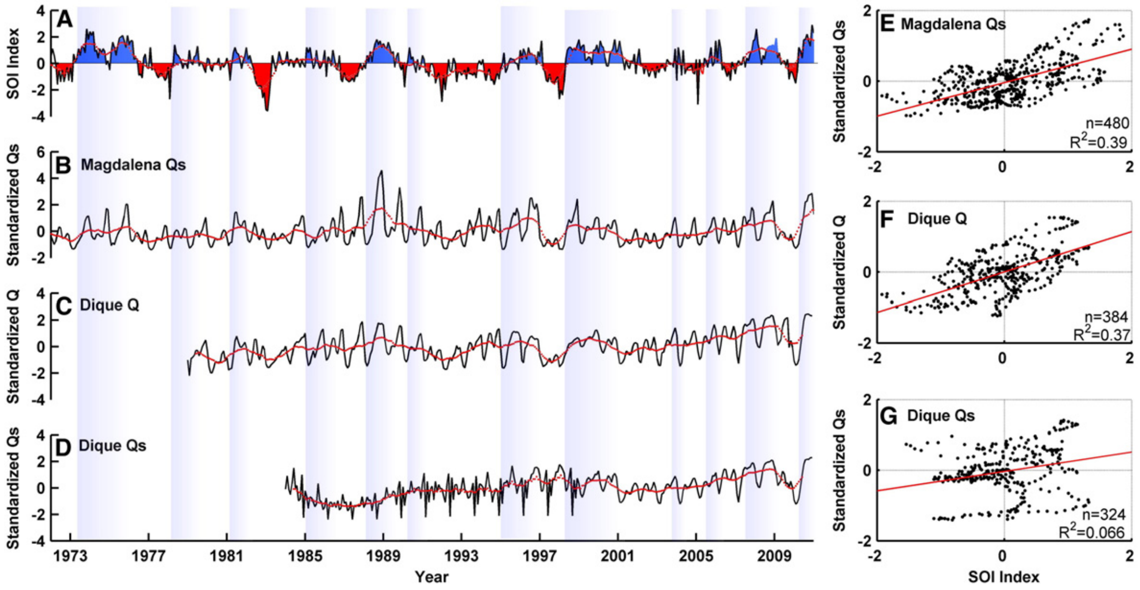

Fig. 3. Standardized series of monthly means (black lines) and low-frequency pass filter (red lines). (A) The Southern Oscillation Index (SOI). (B) Sediment load (*Qs*) of the Magdalena River at Calamar 1972–2011. (C) Water discharge (*Q*) of the Canal del Dique at Santa Helena 1978–2010. (D) Sediment load of the Canal del Dique 1984–2010. (E–G) Scatter plots of regression analysis between standardized series of SOI index and sediment load of the Magdalena at Calamar as well as water discharge and sediment load of the Canal del Dique at Santa Helena.

discontinuities or changes in grain size were observed in the deposited sediments, which are absolutely dominated by silty sedimentation. 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% (Restrepo et al., 2016).

To estimate the periodicities and variability patterns and to distinguish temporal oscillations in fluvial fluxes of the Magdalena River and the Canal del Dique, the continuous wavelet transform was applied on monthly deseasonalized time series of water discharge and sediment load (Fig. 4). Sediment load series of the Magdalena at Calamar show an annual signal during the mid 1970s, late 1980s and 1990s, and at the end of the 2005–2010 period (Fig. 4A). These annual oscillations are significant at the 95% confidence level (Fig. 4D). Similarly, the average variance of sediment load at the 2–8 year band shows two peaks during the late 1980s and 1990s and a progressive upward trend between 2005 and 2010 (Fig. 2). Other 2–4 year oscillation patterns over the periods 1995–2000 and 2007–2010 and a quasi-decadal oscillation between 1985 and 1995 (Fig. 4A) are present, but not all are statistically significant (Fig. 4D). Nevertheless, the conjugation of strong annual, interannual (2–4 y), and quasi-decadal (8 y) signals of sediment load from

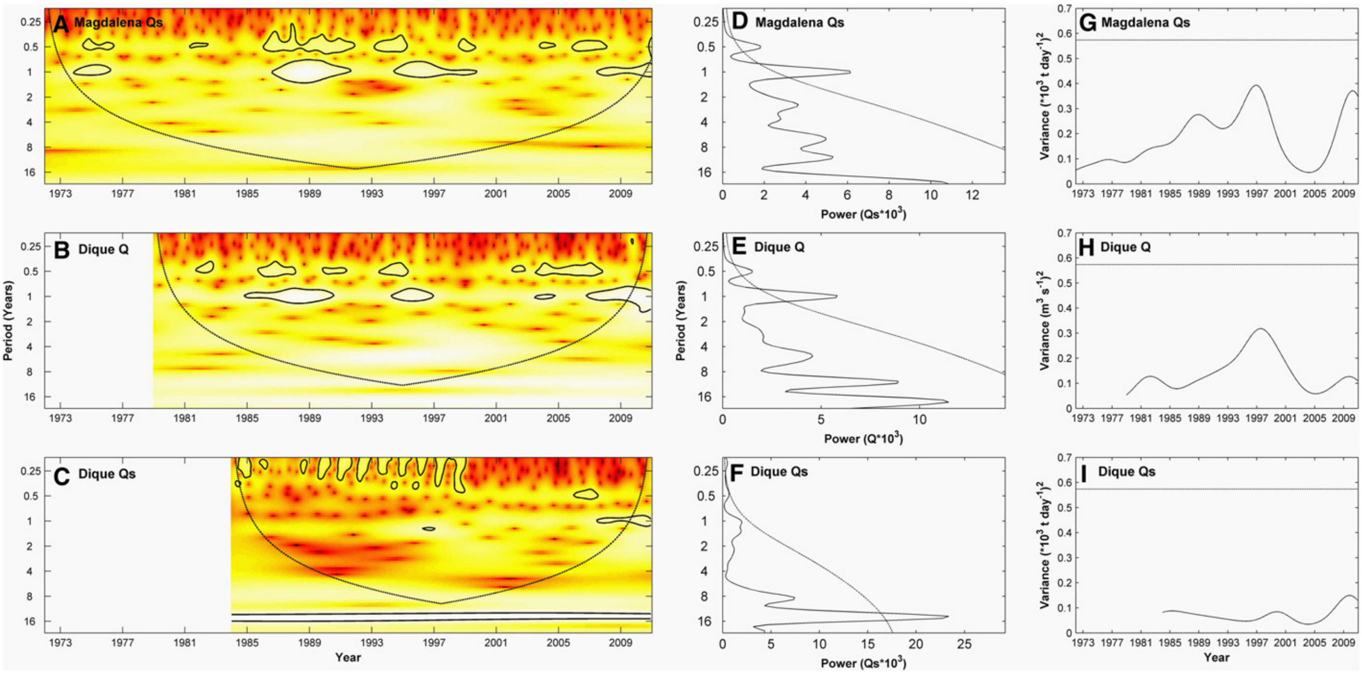

Fig. 4. Water discharge (*Q*) and sediment load (*Qs*) wavelet analysis of the Magdalena River at Calamar and the Canal del Dique at Santa Helena (Fig. 1). (A–C) Continuous wavelet transform spectrum, showing high values of the transform coefficients (white) and the 95% confidence level (dashed line). (D–F) Global wavelet spectrum. (G–I) Power analysis of sediment load in the frequency domain at average variance of 2–8 year band.

the lower Magdalena suggest that the mechanism of sediment fluxes has a large spatial scale.

In the Canal del Dique, water discharge series show an annual signal during the late 1980s and 1990s, and at the end of the 2005–2010 period (Fig. 4B). These annual oscillations are significant at the 95% confidence level (Fig. 4E). The 6-month period appears highly intermittent, but it is more visible in the 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. In contrast, sediment load series of the Canal del Dique exhibit a visible annual component between 1985 and 2007 (Fig. 4C). Longer period oscillations of 2–4 y appear stronger over the 1987–1995 period. A 4–8 year fluctuation was detected over the 1997–2007 interval. In addition, the variance spectrum reveals peaks in sediment flux during the late 1990s and at the end of the 2000–2010 decade (Fig. 4I).

3.3. Prediction of fluvial fluxes into Cartagena Bay

Following the Box-Jenkins methodology, the *SARIMA* $(2,1,12) \times (1,0,1)_{12}$ and *SARIMA* $(1,1,12) \times (1,0,1)_{12}$ were the most accurate numerical approximations for water discharge and sediment load predictions, with covariance proportions of ~0.99. Observed versus simulated water discharge and sediment load fit very well with a coefficient of determination $R^2 = 0.90$ (Fig. 5). *p*-Values of 0.97 in the ARCH test indicated no significant ARCH effects in water discharge and sediment load because of low volatility. Thus, no further ARCH simulation was required.

The dynamic forecasting DFT of water discharge in the Canal del Dique at Santa Helena predicts a mean water discharge of 702.8 $m^3\ s^{-1}$ by 2020, corresponding to an increase of 163.5% with respect to the observed mean discharge of 2010. Maximum values of water discharge at return periods of $T = 2.33$ y and $T = 10$ y are 927.1 $m^3\ s^{-1}$ and 1114 $m^3\ s^{-1}$, respectively (Fig. 6A).

Also, the applied DFT forecasting predicts a mean sediment load of the canal at Santa Helena of 17.22 Mt y^{-1} by 2020, corresponding to an increase of 222% with respect to the mean load of 6.75 Mt y^{-1} estimated during the 2000–2010 period. Maximum values of sediment flux of 22.89 Mt y^{-1} and 19.89 Mt y^{-1} are predicted over return periods of $T = 2.33$ y and $T = 10$ y, respectively (Fig. 6B).

Based on calibration curves of sediment load at different outlets of the Canal del Dique in Barbacoas and Cartagena bays (Fig. 1; Corredor and Castro, 2008), a conceptual model of sediment flux distribution was developed (Fig. 7). Overall, Cartagena Bay receives 36 and 23% of the total sediment load during wet and dry climatic conditions, respectively. In this regard, the Canal del Dique delivers 2.6 and 1.3 Mt y^{-1} of sediments into Cartagena Bay during wet and dry periods, respectively (Fig. 7).

Based on these established percentages of sediment fluxes into Cartagena Bay, the applied DFT forecasting by 2020 predicts different scenarios of sediment flux into Cartagena Bay, including mean, maximum, and minimum fluxes of 5.1, 8.24, and 2.1 Mt y^{-1}, respectively (Fig. 6C). By 2020, maximum sediment fluxes into the bay will witness increments of ~317% (Fig. 6C).

3.4. Connections between fluvial fluxes and upstream human impacts

The Magdalena may be one of the few medium-sized world rivers experiencing such strong increases in sediment load during the last decade. The intradecadal fluctuations of sediment load are more pronounced at the end of the 1980s and 1990s and for the 2005–2011 year-period (Figs. 2 and 4). Overall, the Magdalena drainage basin has witnessed an increase in mean erosion rates from 550 t $km^{-2}\ y^{-1}$ before 2000 to 710 t $km^{-2}\ y^{-1}$ for the 2005–2011 period. Consequentially,

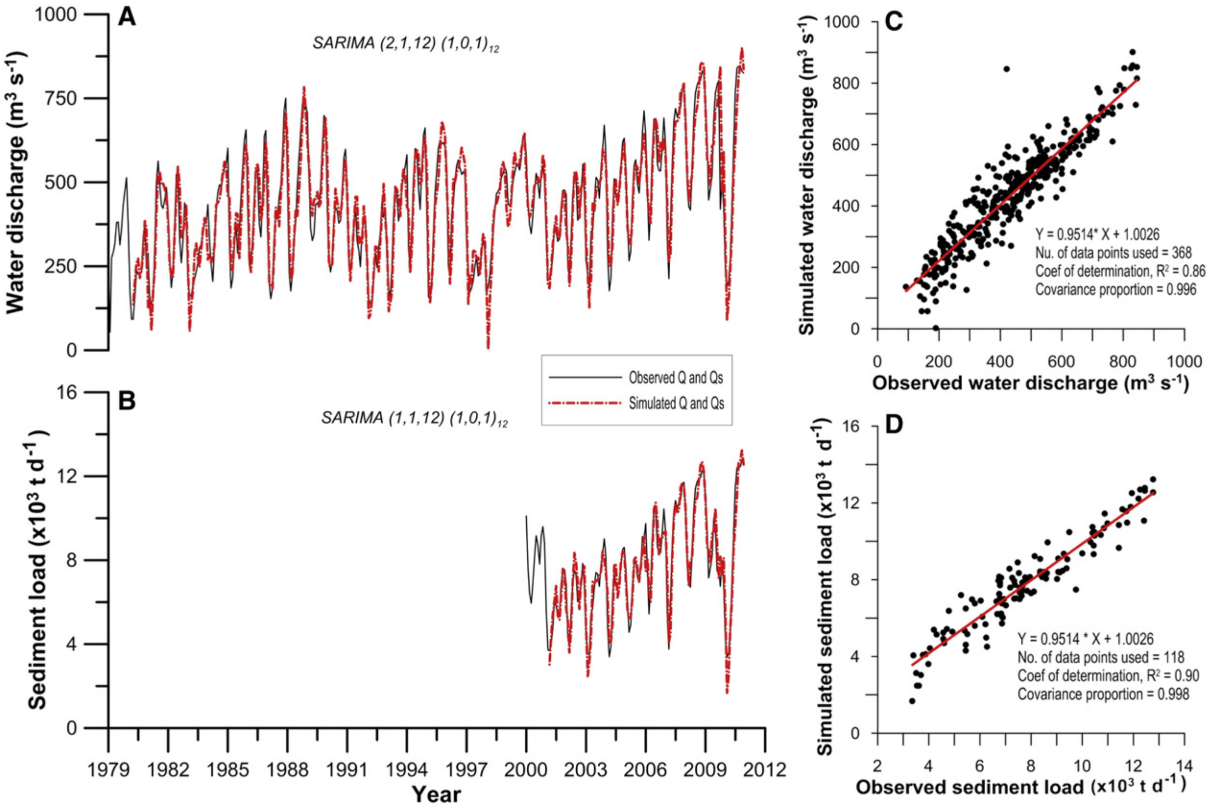

Fig. 5. (A–B) Observed and SARIMA model simulated times series of water discharge (*Q*) and sediment load (*Qs*) for the Canal del Dique. (C–D) Scatter plots of observed water discharge and sediment load versus SARIMA model simulated fluxes.

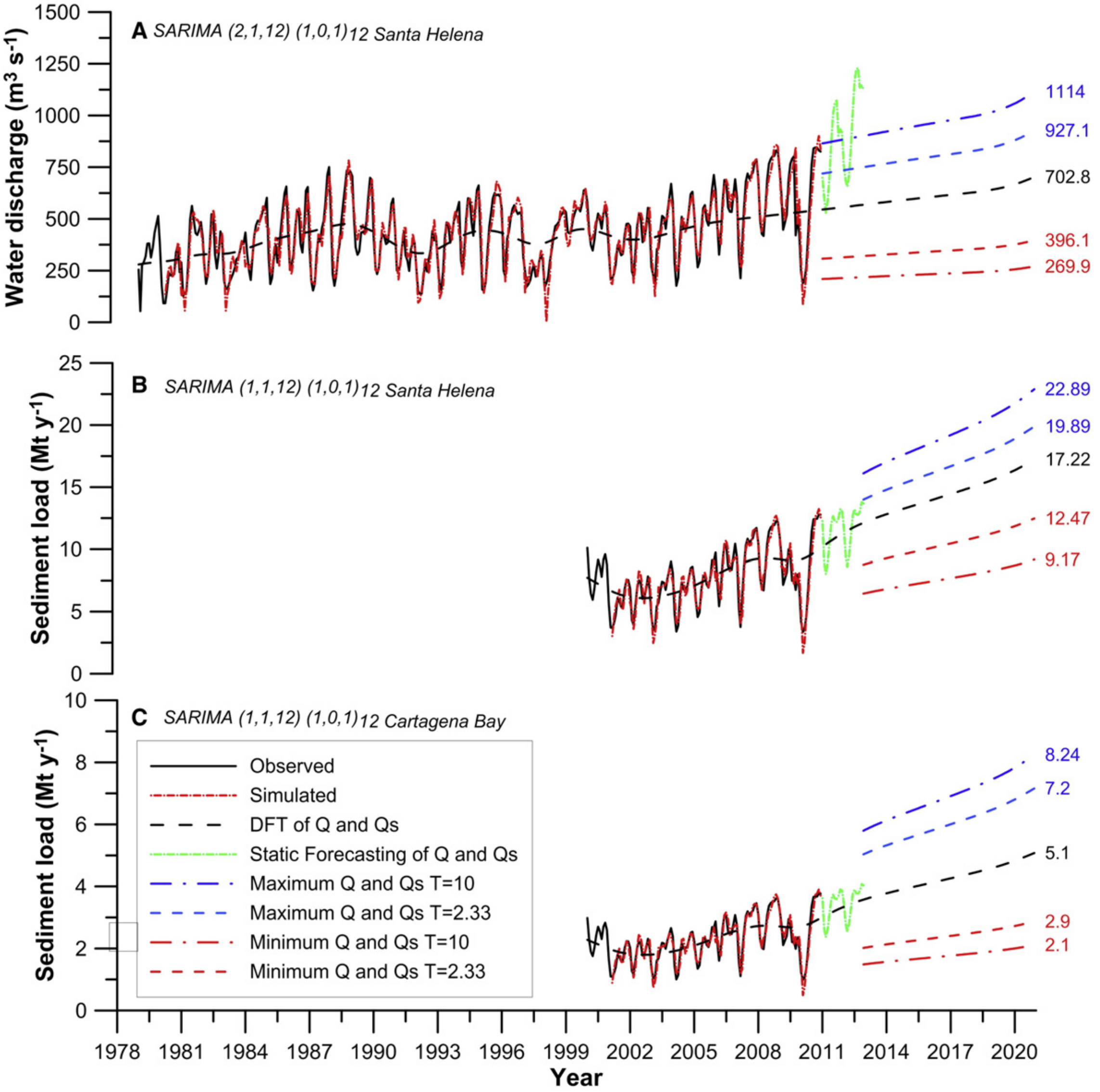

Fig. 6. Dynamic forecasts of water discharge (A) and sediment load in the Canal del Dique at Santa Helena (B) and Cartagena Bay (C) (Fig. 1). Maximum (blue) and minimum (red) fluxes at return periods of 2.33 and 10 y are shown.

the average sediment load for the whole Magdalena basin increased 44 Mt y^{-1} during the last decade (Restrepo et al., 2015).

Besides the natural factors that lead to excessive erosion, including steep slopes, tectonic activity, available runoff for erosion and sediment transport, and morphological conditions, forest cover in the Colombian Andes has greatly decreased because of population expansion and changes in land use. The first studies assessing the human impact on soil erosion in the Andes of the Magdalena basin (Restrepo and Syvitski, 2006; Restrepo et al., 2006) showed that most of the erosion for the whole basin can be explained by natural variables, including runoff and maximum water discharge. These two estimators explain 58% of the variance in erosion. Further temporal analyses of sediment discharges and land use show that the extent of erosion within the Magdalena has increased over the last 10–20 y. Many anthropogenic influences, including a 44% decrease in forest area in a 20-year period, a 75% increase in agriculture and pasture, poor soil conservation and mining practices, and increasing rates of urbanization, have accounted for the overall increasing trends in erosion on a regional scale. No doubt that human activity in the Andes of Colombia has been an effective agent in altering the landscape, affecting erosion rates and therefore fluvial sediment fluxes to the coastal zone.

Further time series analysis of sediment load for 1980–2000 in 21 main tributaries of the Magdalena River indicates that 17 watersheds (68% of the drainage basin area) included in the regional database show increasing trends, whereas 12 locations or 31% of the land basin area display decreasing trends. Only three stations, representing 1% of the drainage basin area, show no significant trend in sediment load. Most of the tributaries in the upper Magdalena basin have experienced significant increases in sediment load over the 1990–2000 period. Also, the Opón River, located roughly in the middle of the Magdalena basin on the eastern side, has witnessed sediment load increases starting since the 1990s (Restrepo and Syvitski, 2006; Restrepo, 2015).

Modified M-K tests were applied to test the statistical significance on upward and downward trends in sediment load for the Magdalena tributaries during the 1980–2010 period (Fig. 8). Some tributaries witnessed upward trends during the 1980s, 1990s and post-2000, including the Páez, the Carare, the Gualí, the Opón, the Sogamoso, the Guarinó, and the Suárez (Fig. 8A). The Cauca River, the main Magdalena tributary, saw its sediment loads increase by 30% from 1979 to 1999. Between 1979 and 1989, the average sediment load of the Cauca was 44 Mt y^{-1}. Since 2000, its average load has increased to 59 Mt y^{-1}. Statistically significant upward trends at the 95% confidence level are seen

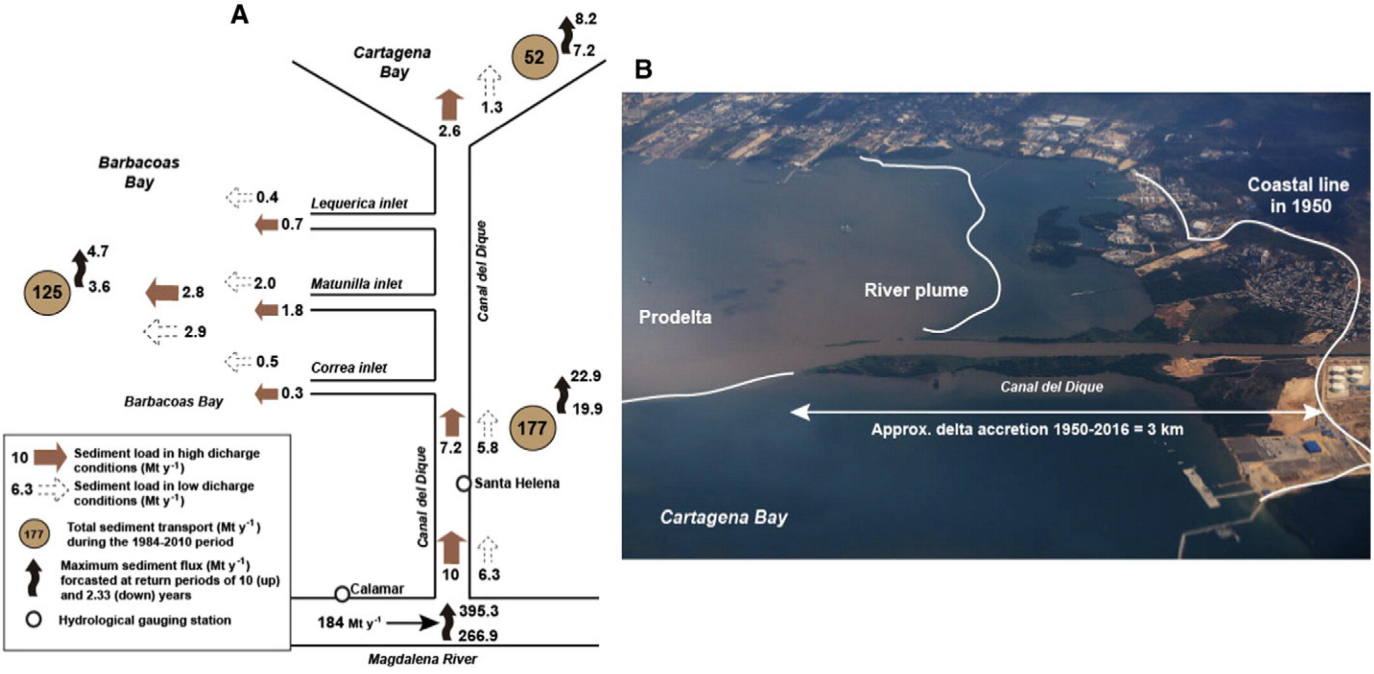

Fig. 7. (A) Conceptual model of sediment flux distribution in the Canal del Dique based on calibration curves of sediment load at different outlets of the Canal in the bays of Barbacoas and Cartagena (Fig. 1; Corredor and Castro, 2008). (B) Aerial photograph of Cartagena Bay showing the delta formed by the Canal del Dique, the turbid plume of sediments and approximate accretion rate since 1950s.

for the Cauca between 1995 and 2002 as well as during the 2005–2010 period (Fig. 8B).

Additional M-K tests on sediment load series for the 21 tributary systems during the 2005–2010 period show that six tributaries, representing 55% of the analyzed Magdalena basin area, have witnessed increasing trends in sediment load (Fig. 8E). The Cauca experienced an increase in sediment load of 1.7 Mt y^{-1}. Further analysis of standardized sediment load series reveals that 12 tributary basins experienced more pronounced positive deviations during the 2000–2010 period compared to the pre-2000 period.

Recent assessments on global deforestation show that the tropics account for 58% of the net global forest loss (e.g., Ferretti-Gallon and Busch, 2014). A recent deforestation study spanning over 34 tropical countries that take into account the majority of the global land of humid tropical forests (Kim et al., 2015) indicates a 62% acceleration in net deforestation from the 1990s to the 2000s, contradicting a 25% reduction reported by FAO (2010). Analyzing the data presented in this study, net forest loss in Colombia peaked from 1990 to 2010, a period of an exponential increase in forest clearance, from 170,000 ha y^{-1} between 1990 and 2000 to 499,000 ha y^{-1} during the 2005–2010 year-period (Fig. 8F). After Brazil, Colombia has the highest deforestation rate of all Latin American countries.

Land cover change analysis obtained in the classification of the 1980 and 2000 MSS and TM Landsat images shows that land cover in the Magdalena basin has undergone considerable change. The forest cover decreased by 40% over the period of study, while the area under agriculture and pasture cover increased by 65% during the same 20-year period (Restrepo and Syvitski, 2006; Fig. 8C). Additionally, many Magdalena subcatchments, including the Cauca, Opón, Suarez, Negro, and Páez rivers, witnessed an order of magnitude increase in their deforestation rates when compared to other tributaries during the 2005–2010 period. The total forest clearance in the Magdalena basin of 510,565 ha between 2005 and 2010 represents 24% of the combined deforestation in Colombia (Restrepo et al., 2015). This period represents the highest peak of forest loss on record in Colombia (Fig. 8D; Restrepo, 2013; Kim et al., 2015).

No doubt that deforestation in the Andean section of the Magdalena watershed has strongly increased soil erosion and sediment transport to the coastal zone. Results from numerically estimating the amount of sediment explained by deforestation in the Magdalena basin shows that 9% of the sediment load in the Magdalena River basin is due to deforestation. Therefore, approximately 482 Mt of sediments were produced due to forest clearance in the Magdalena River catchment in the last three decades (Restrepo et al., 2015).

Regional analysis of land use and sediment load trends appears to indicate that the extent of erosion within the Colombian Andes has severely increased over the last 30 y (Restrepo et al., 2015). For instance, the last decade has been a period of increased pulses in sediment transport as seen by the statistically significant trends (Fig. 8). Meanwhile, this period has also been a time of a dramatic increase in forest clearance (241%), from 170,410 ha y^{-1} between 1990 and 2000 to 498,870 ha y^{-1} during the 2005–2010 period (Fig. 8F).

Overall, trends in sediment load of the Magdalena River at Calamar and the Canal del Dique at Santa Helena (Figs. 2 and 4) are in close agreement with the observed upstream trends in sediment flux and associated human erosion caused by deforestation (Fig. 8). The last decade has witnessed stronger increments in fluvial fluxes to Cartagena Bay, which clearly coincide with associated human impacts on the Magdalena basin.

4. Discussion

4.1. Fluvial fluxes and temporal variability

Our results of water discharge for the Magdalena is in agreement with the results shown by Restrepo and Kjerfve (2000b). For example, their estimate of 7200 m^3 s^{-1} for the Magdalena at Calamar before 2000 is very close to our value of 7156 m^3 s^{-1}. In addition, our value of 7783 m^3 s^{-1} after 2000 is of the same order as the estimate presented by Restrepo et al. (2014) of 7391 m^3 s^{-1}, which did not include the anomalous La Niña year 2011. With respect to pre-2000 and post-2000 discharges in the Canal del Dique, our estimates of 390 and

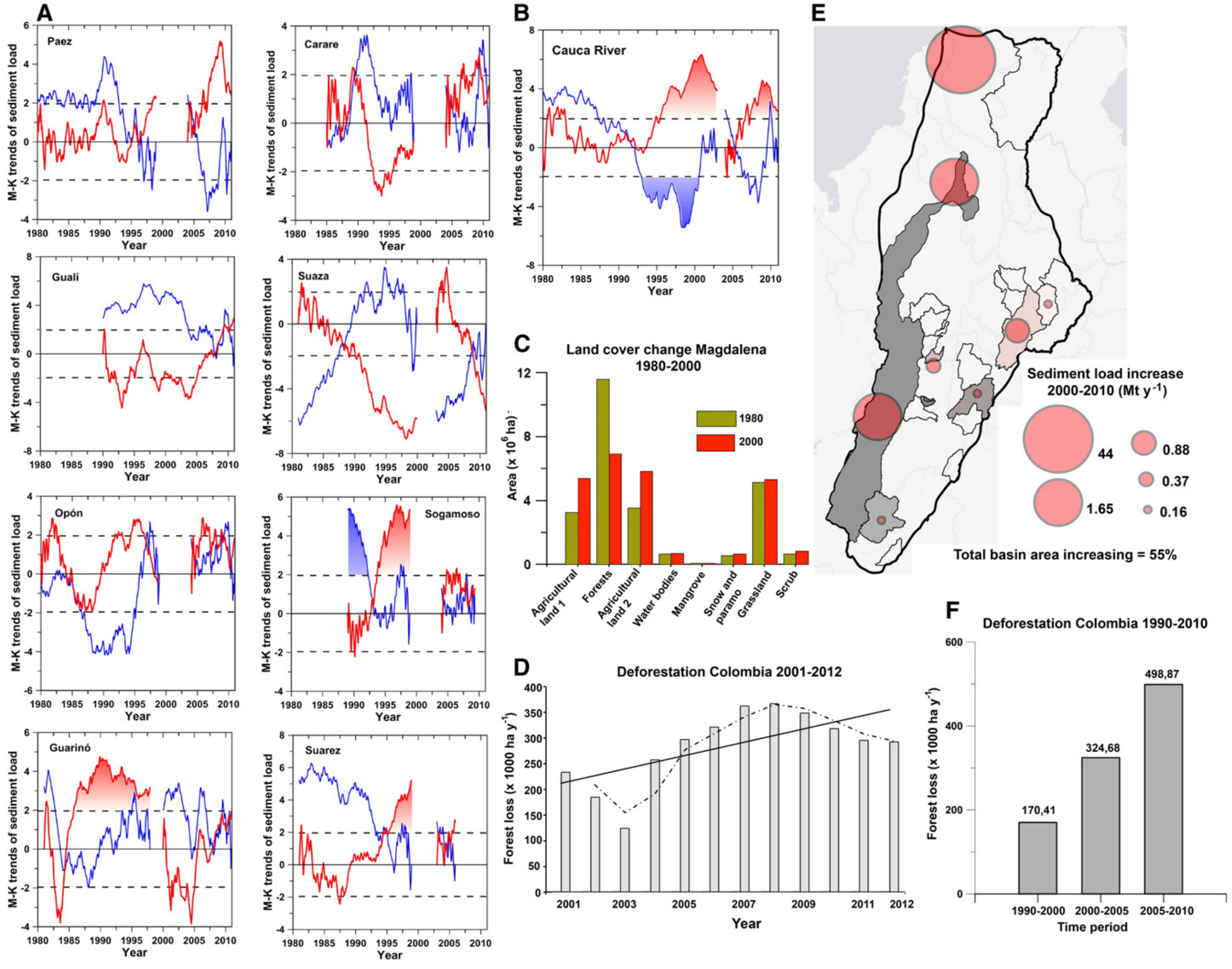

Fig. 8. (A) The M-K trends of sediment load for selected Magdalena tributaries (A) and the Cauca River (B). Progressive and retrograde series are shown in red and blue, respectively. (C) Area (in ha) occupied by each of the land cover types in the Magdalena basin obtained in the classification of the 1980 and 2000 MSS and TM Landsat images (data from Restrepo and Syvitski, 2006). (D) Deforestation rates in Colombia during the 2001–2012 period (data from IDEAM, 2014 and Global Forest Watch-GFW, 2014). (E) Regions of the Magdalena drainage basin experiencing upward trends in sediment load during the 2000–2010 year-period. (F) Deforestation rates in Colombia during the 1990–2000, 2000–2005, and 2005–2010 periods (data from Kim et al., 2015).

508 $m^3\ s^{-1}$, respectively, are quite similar to those calculated by Restrepo et al. (2014) of 393 and 498 $m^3\ s^{-1}$, respectively. To the best of our knowledge, studies updating the recent values of sediment load for the Magdalena and the canal are not available.

All South American rivers, independently of size, display a strong seasonal signal of discharge and sediment load variability, typically by a factor of 5–10, comparing low to high monthly discharge. The interannual variation of discharge and sediment load associated with the ENSO or El Niño-La Niña cycle can be almost equally great, typically by a factor of 2–4, comparing low to high annual discharges (Richey et al., 1986; Depetris et al., 1996; Vörösmartry et al., 1996; Restrepo and Kjerfve, 2000b). In Colombia, relationships between river discharge anomalies and the ENSO have been found in the Magdalena (Restrepo and Kjerfve, 2000b) and other Caribbean rivers such as the Sucio, Sinú, and Canal del Dique, which exhibit higher water discharge during La Niña and lower flows during El Niño (Restrepo et al., 2014). Further statistical analysis on annual streamflow data and ENSO anomalies show that the ENSO may be responsible for up to 65% of interannual streamflow variability in rivers such as the Magdalena, Cauca, Cesar, Rancheria, and Sinú (Gutiérrez and Dracup, 2001; Restrepo et al., 2014). In addition, the annual and interannual variabilities of soil moisture in drainage basins are highly intertwined during strong El Niño and La Niña events, with greater positive anomalies during La Niña (Poveda et al., 2001; Restrepo et al., 2015).

Previous analysis on the interannual variability of sediment load of the Magdalena River at Calamar (Fig. 1) showed that an interannual oscillation correlated well with the ENSO cycle. Regression analysis of the low frequency sediment load on the smoothed SOI yielded a coefficient of variation of $R^2 = 0.54$, significant at 95%, indicating that variations in the Southern Oscillation Index (SOI) explain 54% of the variability in sediment load (Restrepo and Kjerfve, 2000b). As noted by Restrepo et al. (2015), major positive deviations of sediment load in 1989, 2000, 2006, 2009, and 2011 coincided with strong La Niña events. Based on the Oceanic Niño Index (ONI), 10 out of 13 La Niña events between 1972 and 2011 witnessed positive deviations in sediment load. Clearly, the Magdalena sediment load is strongly coupled to the El Niño–La Niña cycle, a condition also observed in the wavelet analysis with periodicities ranging between 2 and 7 y (Fig. 4).

The conjugation of strong annual, interannual (2–4 y), and quasi-decadal (8 y) signals of sediment load from the lower Magdalena suggest that the mechanism of sediment fluxes has a large spatial scale. As noted by Restrepo et al. (2014), the presence of these hydrological oscillations indicate that the mechanism of fluvial fluxes has large spatial and temporal scales. Large-scale atmospheric processes and local-scale natural- and human-induced factors (e.g., basin size, relief, vegetation cover, soils, land-use change, deforestation, mining) operate at the whole basin scale and produce strong temporal fluctuations.

4.2. Short-term predictions of fluvial fluxes into Cartagena Bay

Nowadays, various types of sediment flux models exist, and they can be grouped in four main categories: (i) empirical prediction models, (ii) process-based prediction models, (iii) dynamic simulation models, and (iv) stochastic models (Gangyan et al., 2002; Chandramohan, 2006). For example, SEDFLUX can be grouped in the second or third category (process-based prediction model or dynamic simulation models). Usually, the first three categories require a lot of data and primary information over long time periods; although the fourth category, the stochastic models, are numerical approximations where only a time series itself is required to be performed. They can be used to generate synthetic records, forecast hydrological events, detect changes over the time series (e.g., abrupt changes in trends), or fill missing data (Maidment, 1993; Machiwel and Jha, 2012).

Time series analyzing and stochastic modeling were initially developed for economical sciences; however, numerous applications have been developed on hydrology such as analysis on rainfall data (Henderson, 1989; Astel et al., 2004), stream flow data (e.g., Radziejewski et al., 2000 Fanta et al., 2001; Chen and Rao, 2002), flood data (e.g., Grew and Werrity, 1995; Douglas et al., 2000), and sediment load (e.g., Woolhiser and Blinco, 1975; Jayawardena and Lai, 1989; Higashino et al., 1999; Gangyan et al., 2002; Melesse et al., 2011).

In this study, we used SARIMA stochastic models to generate synthetic data series of fluvial fluxes up to 2020. Longer time series up to 2050 or even up to 2100 could not be simulated for the Cartagena Bay because of the short length of the existing series of fluvial fluxes. Once we consider that the SARIMA model bases its prediction on the orders p, q of the ARMA (auto regressive and moving average) components, our predictions would become redundant the more we exceed the orders p and q. For example, consider the SARIMA model of water discharge where $p = 2$ and $q = 12$ and for sediment load where $p = 1$ and $q = 12$. The value of the month 01 of 2011 is based on the AR component of two months ago (month 10 of 2010), and the MA component of 12 months ago (month 01 of 2010). In the case of sediment load, the AR component is based on the past month (month 12 of 2010), and the MA is based on the values of 12 months ago (month 12 of 2010). That is to say, the more ahead we go on our forecast, the forecasted values would be farther from our starting period in the year 2010 and would be predicted using synthetic values, which at the same time are predicted from other synthetic values. If we go 50 or 100 y into the future, our forecast would be based on purely synthetic time series of the years 49 or 99. Then, if we want to keep predictions close to reality, we must use our real records.

While longer-term predictions would naturally be preferable, these short-term projections are still valuable for various applications. The 2020 projections have supported environmental management in the zone, emphasizing the urgency for mitigation actions to be taken before sediment loads increase dramatically and potentially further impact the coastal ecosystem. These short-term projections are also being applied to coastal modeling studies of sediment dispersion (e.g., three dimensional simulation of the bay's hydrodynamics using the MOHID model), allowing research to focus on the future impacts on receiving waters, which also supports decision makers with knowledge on the immediate need for upstream watershed management.

The time period until 2020 is also of particular interest because of an ongoing hydraulic intervention in the Canal del Dique that is being implemented by the National Adaptation Fund (http://sitio.fondoadaptacion.gov.co/). This intervention plans to construct hydraulic doors along the Canal del Dique to reduce its flow of by ~50%. However, the plans of this upstream intervention have not considered trends of future increases in water and sediment fluxes. Various potential results of reducing the Canal's flows with hydraulic doors need data on sediment flux scenarios such as the trends shown in the present study. For example, the flow reduced by the flood doors could be balanced by the increasing trends with the result that current conditions for the coastal receiving waters continue. Another potential result could be that water discharge is reduced by the hydraulic doors, but that sediment concentrations increase because of the observed trends. These outcomes remain to be seen, but this highlights the importance of the short-term projections until 2020 presented in this study.

4.3. River basin-coast interactions

According to Land Ocean Interactions in the Coastal Zone II Science Plan and Implementation Strategy (LOICZ, 2005), the challenge is to bring together the combined expertise of natural and social sciences to study the river basin and coastal zone as one system in order to address global perspectives of water and sediment loads into the coastal zone and the impact of human activities on natural systems. Thus, one of the principal rationales of LOICZ II is that river basin-coast interactions reflect a coupled human and natural system, and activities should focus on the magnitude and variations in land-derived material loads to the coastal and on the implications of these fluxes and changes on human uses and coastal functioning.

Sediment flux of the Magdalena River has witnessed increasing trends during the last three decades because of poor environmental management of the Andean catchments in Colombia and the lack of perception by government authorities on how a fluvial system works and on the river-coast interactions (the cascade-interlinked effect between fluvial basins and coastal systems). Thus, deforestation in a remote place in the Andes also produces impacts in the floodplains of the river or even in the coastal-marine zone. This situation is even worse when engineers built artificial channels such as the Canal del Dique without understanding the environmental interactions.

The Magdalena and its tributaries have experienced increasing trends in sediment load during the 1980–2010 period. Many anthropogenic influences — including a forest area decrease of 60% in a 30-year period, an agricultural and pasture area increase of 65%, poor practices of soil conservation and mining, and increasing rates of urbanization — may have accounted for the overall increasing trends in sediment fluxes to the Caribbean and Cartagena Bay (Restrepo et al., 2015).

Increasing sediment fluxes of the Magdalena River have strongly impacted coastal ecosystems (Restrepo and Alvarado, 2011; Restrepo et al., 2016). The impacts of heavy sediment loads and fresh water discharges into Cartagena Bay have greatly contributed not only to the total disappearance of coral formations but also to a considerable reduction in abundance of seagrass beds in the bay and neighboring areas. From nearly 850 ha of seagrass existing in the bay in the 1930s, only 76 ha remained in 2001, which is <8% of the original cover. The loss rate within the bay was particularly high in the 1940s and 1950s (about 42 ha y^{-1}), so that by 1957 >60% of the seagrasses existing in 1935 had been already eradicated, with the great majority at the entrance to the Canal del Dique in the southeastern sector of the bay (Díaz and Gómez, 2003; Restrepo et al., 2006b).

In addition, coral reefs in the Cartagena region have been chronically exposed to river sediment plumes (total suspended sediments, TSS) from the Magdalena River and the Canal del Dique over the last decade. The Magdalena River plume TSS concentrations witnessed maximum TSS values of 62.3 mg/l observed in coral reef waters of the Rosario Islands National Park, 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 shelf 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 (Restrepo et al., 2016).

The coastal zone of Cartagena, Colombia, has a limited capacity for water resource management, as evident in the degradation of its coastal water quality, which is affected by various pollution sources along the coast, such as the already mentioned continental flux from the Canal del Dique, as well as domestic and industrial wastewater. Pollution related problems with runoff are expected to increase in the near future because of climate change, as related to storm intensification (Hoyos et al., 2013), and caused by human development, as related to watershed deforestation and structural alterations to the Canal del Dique (Restrepo et al., 2015).

The lack of data has hampered the effective implementation of water resource management plans oriented toward prevention or mitigation of the adverse effects of hydrologic events. In recent years, such plans have gained importance because of an increase in the frequency, duration, and intensity of hydrological events such as floods and droughts experienced during the La Niña event of 2010–2011, the worst floods on record in the lower Magdalena floodplain and the Canal del Dique (Hoyos et al., 2013; Restrepo et al., 2014).

4.4. Fluvial fluxes of the Magdalena River into the Caribbean Sea

Most of the Magdalena sediment trapping occurs in the lower reach before Calamar, the Momposina (Mompox) depression wetlands. This avulsive anabranching flood basin with an area of 25,000 km^2 is at least 55 m thick with Holocene deposits (Smith, 1986; Latrubesse, 2015). Previous findings estimate that the foreland basin-trapping zone of the Momposina depression may store ca. 21 Mt y^{-1} of suspended sediment (Restrepo et al., 2006b), while an estimated 53% of the incoming bedload is deposited in the Magdalena foreland (Smith, 1986). Farther downstream from Calamar, the Magdalena has been efficiently channeled and most of its lateral connections with floodplains were cut off during the last five decades (Restrepo, 2008). Currently, ~174 Mt y^{-1} of suspended sediments reach the Magdalena River delta.

Monthly series of sediment load 1972–2011 at Calamar reveals significant upward trends in annual sediment load during the mid-1980s, 1990s, and post-2000 (Fig. 2D). Between 2000 and 2010, the annual sediment load increased 33% with respect to the pre-2000 period and more positive deviations are observed during this period (Fig. 2D). The Magdalena drainage basin has witnessed an increase in mean erosion rates from 550 t km^{-2} y^{-1} before 2000 to 710 t km^{-2} y^{-1} for the 2000–2010 period. The average sediment load for the whole Magdalena basin increased 44 Mt y^{-1} during the last decade. Similar to the sediment load trends of the Canal del Dique, the Magdalena sediment flux to its delta has also increased considerably during the last decade. During the last 16 y, the Magdalena has delivered ~2784 Mt of sediment to the Caribbean coast.

The Magdalena transports 30 Mt y^{-1} of dissolved materials into the Caribbean, with a specific transport rate of 117 t km^{-2} y^{-1}. It is the Colombian river that contributes by far the highest P and N fluxes to the sea, with total phosphate and nitrate fluxes up to 186 × 10^3 t y^{-1} and 47 × 10^3 t y^{-1}, respectively (Restrepo and Kjerfve, 2004). The coastal aquatic systems, including the Magdalena coastal lagoon, the Ciénaga Grande de Santa Marta, are now affected by hypoxia, eutrophication, salinisation, and contamination by nitrate, metals, and persistent organic pollutants. Phosphate (PO_4^{3-}) and nitrate (NO_3^-) increases are observed in most coastal lagoons exposed to human pressure. Their sources are multiple. Since the 1950s, the use of nitrogen and phosphorous in Colombia (as fertilizers) and in food, detergent, and other industries have resulted in a rapid increase of fluvial N and P fluxes, now exceeding the pristine levels by a factor of 10 (Restrepo, 2008).

What happens to the Magdalena dissolved fluxes when they empty into the Caribbean Sea has not been analyzed. The influence of Magdalena River fluxes on coastal ecosystem processes is poorly understood because of insufficient data on pristine water quality or habitat status at undisturbed sites. Nevertheless, Magdalena is the major collector of municipal and industrial wastewaters in Colombia. Urban, agricultural, mining, and industrial waste inputs from the Magdalena basin have aggravated the conditions of the Ciénaga Grande lagoon and coastal ecosystems. Biodiversity has been reported to be considerably lower in the area affected by mangrove mortality as well as in the coastal zone (Restrepo, 2008).

5. Conclusions

We have analyzed the interannual trends of water discharge and sediment load from the Magdalena River-Canal del Dique system into Cartagena Bay, with an emphasis on the tendencies of fluvial contributions during the past four decades. Overall, both systems show significant trends in water discharge and sediment load records; however, during the 2000–2011 period, 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.

Wavelet analysis of fluvial fluxes revealed annual, interannual (2–5 y), and quasi-decadal (8–16 y) periodicities. The presence of these hydrological oscillations indicates that the mechanism of fluvial fluxes into the receiving estuarine systems has large spatial and temporal scales. Large-scale atmospheric processes and local-scale natural- and human-induced factors (e.g., basin size, relief, vegetation cover, soils, land-use change, deforestation, mining) operate at the whole basin scale and produce strong temporal fluctuations.

During the last decade, the Magdalena drainage basin has witnessed an increase in erosion rates of 33%, from 550 t km^{-2} y^{-1} before 2000 to 710 t km^{-2} y^{-1} for the 2000–2010 period. The Magdalena may be one of the few medium-sized world rivers experiencing such dramatic increases in sediment load during the last decade. For instance, an increase of 44 Mt y^{-1} during the 2005–2011 period represents 60% of the Orinoco annual load and at least 7% of the annual Amazon suspended sediment flux (Syvitski and Milliman, 2007; Restrepo, 2013).

When discussing possible connections between observed trends-oscillations of fluvial fluxes and upstream human activities, trends and fluctuations in sediment load are in agreement with the detected increases in deforestation and other economic activities that promote sediment production. For instance, steep upward increases in sediment load and clear pulses in the wavelet spectrums are present during the periods of major human intervention, including the 1970s, 1980s, 1990s, and 2000s, as well as during the 2005–2011 period. The conceptual model of sediment flux distribution developed for the Canal del Dique and associated estuarine outlets indicates that Cartagena Bay receives 36% and 23% of the canal's total sediment load during wet and dry conditions, respectively. During the 26 y of monitoring, the Canal del Dique has discharged ~177 Mt of sediment to the bays of Barbacoas and Cartagena. The combined sediment load discharged into Cartagena Bay during this same period is 52 Mt.

The developed SARIMA models for the Canal del Dique at Santa Helena predict increases in water discharge and sediment flux of 164% and 222%, respectively, by the year 2020. Meanwhile, sediment fluxes into Cartagena Bay will witness increments as high as 8.2 Mt y^{-1} or ~317% by the year 2020.

Estimating the balance between increasing and decreasing water discharge and sediment loads is of the utmost importance for sound coastal zone and resource management (Syvitski, 2003). The exercise presented here, assessing the net combined effects of fluvial discharge-related stressors into Cartagena Bay, will be used in related studies to identify levels of water pollution and dispersion mechanisms. Also, the findings presented here are useful for addressing relevant questions at global and regional scales (Restrepo, 2008): (i) What are the key controlling factors that define the discharge of water and sediments through the river system and how have natural and man-induced changes in the last 30 y altered the transport rate of river fluxes? (ii) Which factors control sediment transport from the basin in the presence of extensive man-induced alterations and land use change? (iii) How have changes in river fluxes and human land development altered the coastal ecosystems during the past three decades, and what can be expected during the next decades? The research associated with these questions provides a preliminary framework for quantifying and assessing the impacts of natural and man-induced basin changes in the coastal zone.

Overall, this study demonstrates that weak environmental planning in the Andes that generates more sediment production in the upstream basins, in addition to wrong fluvial hydraulic interventions (e.g., Canal del Dique), are factors that exacerbate sediment transport in the Canal del Dique, a condition that creates impacts on coastal-marine ecosystems. Coastal management in the Cartagena region may only be effective when land and marine-based stressors are simultaneously mitigated.

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